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A PHENOTYPIC AND GENETIC ANALYSIS OF ENERGY BALANCE IN DAIRY COWS

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B.Sc. (Nottingham University)

A thesis submitted in fulfilment of

the requirements for the degree of

Doctor of Philosophy

University of Edinburgh

2003

Declaration

I declare that this thesis is my own composition and that the research described in it is my own work, except where otherwise stated.

Michael P Coffey, 2003

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ACKNOWLEDGEMENTS

Throughout this thesis, I have used data from the Langhill Dairy Research Centre located at the University of Edinburgh Langhill Farm. The long-term selection trial running at this farm has been funded largely by the Scottish Executive Environment and Rural Affairs Department (SEERAD) and in some part by BBSRC. I thank SAC, University of Edinburgh and SEERAD for the use of their data and I thank SAC for partly funding this PhD. I also thank Defra for funding the feasibility study on automatic condition scoring in Chapter 2. Colleagues who worked with me on that project at Silsoe receive financial support from BBSRC and Defra.

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Of course, I could not have completed this thesis without the input, on all fronts, from my supervisors Professor W G Hill, Professor G Simm and Dr S Brotherstone who stuck with me when all looked lost and it seemed I would never make a scientist.

PREFACE

I have made the formal acknowledgements that conform. I would now like to thank in my own way, those who helped me make it through.

Being both a physically and mentally mature student has a number of benefits. Aside from the student card that gets you into the Museum for only £1.50 and the Cinema for £3.50, being mature means you have many friends and acquaintances that have contributed to your life and made you the well-rounded person you are. I cannot list them all for they are legion. However, some stand out for their recent or long-term association. Friends from college, Da and Heath, Spunge, Andrew and Nige spring to mind. We have roasted many pigs and talked rubbish under the stars. My old friends Duncan and Marie Spring helped me begin the road to science whilst William and Marion Ley and Ken and Rebecca Proctor being farmers provided my source material. They unwittingly served as test beds for my ideas and William in particular gave me some splendid ideas. Duncan and Carolyn Todd helped me a great deal along the road, many times in a drunken stupor on a Saturday night. As a result, I now know George, Willy, John and their respective partners from Ayrshire and George introduced me to Annie the Heifer.

New friends made in Edinburgh - Beatriz, Geoff and Marie, Santiago and Carlita, Xulio and Carolina, Elly and El Pajaro form a contingent who, like me, enjoy the only indoor barbecue in the whole of Edinburgh. We BBQ indoors all year round and fish the North Sea. I have repaired many household items and had many fine dinners at the Visschers. Naomi is truly a fine cook. Geoff has been a cultural mentor for me, slowly reducing my politically incorrect gaffs to a minimum and has politely looked at my graphs whenever and wherever they appeared. The Sporting ICAPB football team has been a source of great enjoyment and I have performed near miraculous feats in goal, been a firm but

fair referee, a solid defender and tireless mid-fielder. I thank the boys of the team for putting up with me and the talk I talk at half-time.

I have formally acknowledged my supervisors but that does them no justice. Unusually, I have known my supervisors for a very long time - Bill almost all my working life and Geoff and Sue most of it. I have enjoyed working with them all that time as colleagues and especially through the writing of this thesis as both student/supervisor and as friends. I look forward to continuing to do so. Given what they started with, it seems a miracle they persisted and nurtured me to this point with great patience and fortitude. I sincerely thank all three, particularly Sue 'The Doc' Brotherstone who needed the greatest patience.

Of course I thank my mum, the unsung hero. Finally, thanks go to Dan and Jody, the loveliest people in the whole world who both have unwittingly helped me to achieve this and to whom I dedicate this thesis. I also thank you Lauren for everything you have given me.

PUBLICATIONS

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ABSTRACT

In dairy cows, the failure or unwillingness to eat sufficient in early lactation when yield is high leads to a state known as negative energy balance (NEB). In this state, cows mobilise body tissue mostly in the form of body lipid in order to make up the difference in energy available from feed ingested and that required to sustain obligatory requirements, such as maintenance, and milk production. A large NEB is an undesirable state since it is associated with increased disease and reduced fertility.

Body lipid content can be predicted from visual assessment of the tailhead of cows using a system known as body condition scoring (BCS). Changes in this score over time can therefore be used to predict body lipid changes. I investigated the feasibility of automating the process of collecting condition score using a digital camera and laser lights. The correlation between CS and shape over the tail-head was 0.55 suggesting that it may be possible in future to include digital images in an automated and integrated dairy farm management system.

Using random regression analysis, I analysed changes in milk production, feed intake, liveweight and BCS over one to three lactations and calculated energy balance from these daily predictions. These analyses showed that energy balance can be predicted from body measurements without the need to measure feed intake making it practical to use nationally. Using these techniques enabled the genetic analysis of large volumes of field data to predict daily breeding values for energy balance for 1250 progeny test sires. Substantial genetic variation was found in energy balance profiles. The mean total daughter body energy loss at day 305 of lactation was 779 MJ (SD=224 MJ), equivalent in energy terms to about 189 kg milk. Future selection indices may contain an adjustment for the amount of body energy used to support the milk production of a bulls' daughters leading to a more complete assessment of the utility of a bull.

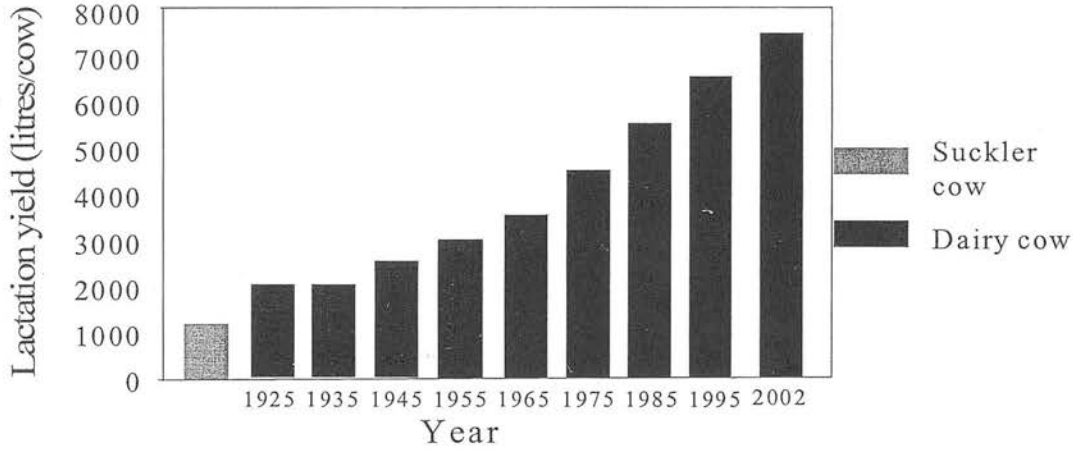
Analysis of data from the Langhill Dairy Research Centre demonstrated that there are differences in the way dairy cows of differing genetic merit for production mobilise body lipid to support lactation and that the amount of concentrate fed also affects the recovery of lost body lipid. Select cows contained about 3200 MJ less energy than control cows at the end of the third lactation and lose and gain body lipid in a cyclical way. Parameters of these curves may be used in future selection indices to allow selection of genotypes that have profiles of body lipid loss and gain commensurate with high yields and long herd life. This may also be useful in future when selection indices contain more traits and farmers and advisors tailor their management to suit the type of cow. It may also provide guidance on how future selection indices should be developed to incorporate traits such as body lipid, traits that enable the robust cow to thrive over many high yielding lactations.

CHAPTER 1

General Introduction

In response to market forces, milk production per cow has risen in the UK, consistent with the trend observed in most temperate dairying nations (Figure 1.1). The average yield of milk produced by UK milk recorded Holstein Friesians in a standard 305 day lactation was 7600 kg in 2002 (NMR, 2002).

Figure 1.1 Average yield of recorded cows in the UK.

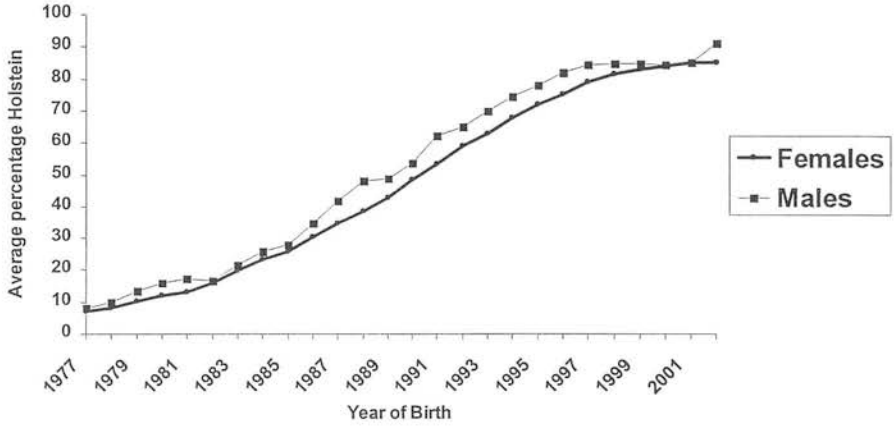


Source: Genetic Improvement of Livestock. G. Simm. (Updated with data from National Milk Records 2002).

Even though it has been estimated that about 60% of the increase in yield in the UK over the period 1990 to 1995 is due to genetic improvement for yield (Lindberg et al., 1998) and whilst there has been a very active breeding programme over the last 20 years, the UK has failed to compete internationally and much of the semen used in the UK is now imported, principally from North America, or from other countries that have themselves imported from North America. Therefore, responsibility for the selection objectives pursued in the UK has been delegated to those companies importing semen from proven bulls into the

UK. Recently, progeny testing has become more competitive in the UK although sires of sons used in these schemes are predominantly of North American origin or the companies progeny testing these sires are pursuing breeding objectives that are at least similar to those in North America. This has resulted in a change in the national UK cow population from virtually pure European Friesian to about 85% North American Holstein genes in 2002 (Figure 1.2).

Figure 1.2 Average percentage Holstein genes in registered calves.



(Source Holstein UK).

Royal et al. (2000) have shown that fertility as measured by conception rate is declining in the UK at the phenotypic level at about 1% per year, despite the best efforts of farmers to maintain or improve it, suggesting a genetic solution is required if cows are to continue to be mated at the farmers' convenience in the future. The trend in health and fertility has been studied in the UK recently using historical data collected as part of the DAISY recording scheme (Kadarmideen et al., 2002). This has shown that whilst the phenotypic trend for some health and fertility traits shows no change, the genetic trend for the same traits are unfavourable suggesting that farmers are compensating for the genetic decline in these traits by improved management. This is clearly unsustainable in the long term since farmers cannot always manage the problem to an acceptable level.

Quite why high yielding cows should be generally less healthy and fertile is not entirely clear. There is an unfavourable genetic relationship between production and disease (e.g. Collard et al., 2002; Cameron et al., 1998; Rauw et al., 1998) and an unfavourable genetic relationship between production and fertility (e.g. Pryce et al., 2002; Veerkamp et al., 2000) suggesting that health and fertility traits should be included in selection indices containing production.

Condition scoring is a technique for estimating the fat content of dairy cows. It relies on visual appraisal of the tailhead area and, optionally, tactile palpation of the loin area. There is a strong relationship between body condition score (BCS) and the fat content of cows (Fox et al., 1999) making BCS a useful management and research tool for assessing fat content and its change. Many studies have also included BCS as a variable and have implicated BCS in the relationship between production and health and fertility (Dechow et al., 2002; Gillund et al., 2001; Pryce et al., 2002; Royal et al., 2002; Veerkamp et al., 2000). Others have attempted to understand the underlying metabolic pathways affected by selection for production and involving changes in BCS (e.g. Taylor et al., 2003; Wathes et al., 2001). These studies have shown that high levels of milk production and associated negative energy balance are related to changes in metabolic parameters including higher levels of urea and decreased levels of insulin-like-growth-factor-I (IGF-I) and insulin. Wathes et al. (2001) suggest that advances in biosensor technology may provide the opportunity to manipulate diets to optimise biological parameters of each cow in the future.

However, given increasing consumer interest in milk production techniques and a desire by farmers to reduce costs of production, selection may be the most effective way to resolve the problem of reduced health and fertility in the long term. If we accept that, for an overall breeding goal of profit, there is not currently a sufficiently complete range of index traits included and that this has contributed to a decline in health and fertility, the question then arises - What do we need to add to our list of index traits to make our assessment of profit in dairy cattle more complete?

Body energy content and its change have recently been the focus of research in many countries leading to a revival of interest in BCS. For example, Veerkamp et al. (2000) showed that the commencement of

luteal activity post calving was correlated to the nadir of negative energy balance whilst Reist et al. (2003) showed that conception to first service was related to energy balance. Collard et al. (2002) concluded that energy balance was correlated to somatic cell count (SCC) and, by implication, to mastitis. These findings suggest that body energy content, or its change, may be a useful addition to future selection indices that include health and fertility costs as well as production. This is the background to this thesis and the hypotheses explored therein depend on the relationship between body energy and overall fitness in dairy cows over their productive lifetime.

In the UK, the inadequate state of national health and fertility data for genetic evaluation was highlighted by Kadarmideen et al. (2002) and suggestions were made to recording organisations regarding changes that would be required before data recorded voluntarily as part of national recording schemes could be used to produce estimates of genetic merit. The low heritability of many health and fertility traits (Kadarmideen et al., 2002) means that genetic evaluations would be of low reliability at current normal progeny test group sizes (about 70 daughters) and for effective use would require progeny group sizes of over 100. An interim alternative to national recording of a wide range of health and fertility traits would be to use body energy content as a predictor of general health status if sufficiently accurate data could be obtained easily, relatively cheaply and in large volume.

Since 1996, Holstein UK have included BCS as a trait recorded at type classification. Using random regression methods of analysis on these data has enabled the calculation of breeding values for each month of lactation (Jones et al., 1999) providing the opportunity in the future to select for animals that have desirable genetic profiles for BCS throughout lactation. The availability of time oriented genetic evaluations will increase the sophistication and accuracy of future selection decisions (Schaeffer and Dekkers, 1994) but will require knowledge of the most appropriate parameter (or parameters) of the curve to include in the decision. Furthermore, the interaction between curves for different traits may change over the lifetime of the animal and so will require the identification of genotypes with the most appropriate lifetime aggregate genetic curve shape for the breeding goal – profit. This is complicated by the fact that profit for different producers may be realised in a different production environment and so require genotypes specific to their circumstances.

The overall objectives of this thesis were to explore the use of energy balance in future selection indices. In Chapter 2, the method by which BCS was estimated at the Langhill Dairy Cattle Breeding Centre was analysed and compared between assessors. I tested the feasibility of collecting BCS measures automatically by using a digital camera and laser lights shining on the backs of cows. The results suggest it is possible to extract shape data relating to BCS from digital images and also that regular calibration of assessors collecting BCS is needed. In Chapter 3, I calculated breeding values for energy balance for each day of lactation for sires used at Langhill farm. Daughters of these sires had daily measurements of feed intake, milk output, liveweight and BCS and so energy balance could be calculated using two different sets of data for the same animals. The objective of this work was to see if energy balance could be calculated using liveweight and BCS records sufficiently accurately because feed intake records are not available at the national level. The curves produced were similar in shape and magnitude suggesting that energy balance calculated from changes in BCS and liveweight could be undertaken if national values for liveweight of cows were available.

In Chapter 4, I report on the way energy balance changes over the lifetime of the animal (or at least the first three lactations) and calculated correlations between early and later life energy balance for cows that all had at least three lactations of continuous feed intake data recorded. In this Chapter, I explored the use of an harmonic function to model three lactation energy balance. This may be a useful way of predicting energy balance in later life when only values in early life are available.

In Chapter 5 I used the techniques developed in Chapter 3 to calculate breeding values for energy balance at the sire level using national type classification and BCS data. I calculated a prediction formula for liveweight from linear type records using data from Langhill. This enabled the prediction of liveweight from national linear type data and, as BCS is also scored nationally, daily predicted transmitting ability (PTA) for energy balance for each sire could be calculated and profiles of energy balance examined. Also in this Chapter I explored the re-ranking of bulls created by making an adjustment to the production PTA for body lipid energy lost in the same lactation. Such adjustments or accounting may be required in future

to enable a more complete assessment of the utility of bulls in a commercial environment that requires attention to cost of production, welfare of cow and impact on environment.

In Chapter 6, I re-examined data from Langhill for cows with feed intake data but this time using a multivariate random regression model analysing data on all three lactations together. This was to determine if genotype by environment interactions exist for energy balance and to examine in detail how cows of different genotypes being fed different energy dense diets utilise body tissue over their lifetimes.

Finally, Chapter 7 contains the general discussion on the relationship between BCS and body lipid content, the strategic use of body lipid by dairy cows, how it is involved with their general health and conclusions on how future selection indices could include body lipid content or changes in body lipid.

CHAPTER 2

A Feasibility Study on the use of Digital Images to Assess Body Condition Score in Dairy Cattle

This chapter is a combination of work undertaken by the author in conjunction with Dr Nigel McFarlane, Dr Robin Tillett and Dr Toby Mottram at The Silsoe Institute and Dr Dave Ross of SAC. The work on condition score analysis is my own whereas that associated with image extraction and analysis was undertaken by these colleagues. Their work is reported in sections 2.4.3 to 2.5.3 of this Chapter. Dr Dave Ross was responsible for constructing and describing the light and camera rig in section 2.4.2.

2.1 INTRODUCTION

Selection mostly for production has led to cows that can, or will, eat only around half of their incremental feed requirements per unit increase in genetic merit for milk production (Veerkamp et al., 1995). Continuing with this selection policy is likely to result in increasing use of body tissue to support milk production and to thinner cows with associated health and fertility problems. This has created increasing interest in body condition scoring (BCS) in dairy cows both as an important management tool and also for use in selection indices.

In early lactation, daily secretion of energy in milk, and its use for other obligatory functions, often exceeds the amount of energy available from ingested nutrients. The cow makes up the difference in daily requirements by mobilising body tissue, most of which is body lipid (Tamminga et al., 1997), leading to a state of negative energy balance (NEB). This is a natural phenomenon in most mammals (Pond, 1999) but modern dairy cows may have inadvertently been selected for a greater willingness to support lactation in this way. It is also known that NEB in early lactation is related to health and fertility problems (e.g. Butler and Smith, 1989; Collard et al., 2000; De Vries et al., 1999 and 2000; Pryce et al., 1999; Veerkamp at al., 2000). Fertility of UK dairy cows in terms of conception rate has been declining phenotypically at 1% per year (Royal et al., 2000) in recent years. The results from these studies emphasise the importance of assessment of body lipid content and its change in dairy cows for day to day management by farmers, and to enable the development of genetic tools for future selection for a favourable body energy state over the productive lifetime of the cow (Chapter 5).

The use of a single measure of a trait in a lactation on a bull's daughters enables profiles for that trait to be constructed using a statistical technique called random regression (Hill and Brotherstone, 1999). This technique was successfully used to construct condition score profiles on bulls' daughters using national data by Jones et al. (1999) and it may be used in future to provide national breeding indexes for BCS derived from field data collected manually (Chapter 5). This enables the best use to be made of single observations, but these data are expensive to collect and provide little utility for on-farm management.

In a market environment that is increasingly aware of quality assurance, consumers or their agents may impose arbitrary limits on a trait, such as BCS, that is perceived to be associated with the welfare of the cow. It is likely that BCS measures will become increasingly important and their use will be more widespread in future dairy production systems. In this case it would be helpful to have objective measures that can be scrutinised by consumers (via supermarkets) and standards bodies.

In the UK, the breed society responsible for the black and white breed (Holstein UK) operate a type assessment scheme that includes BCS as one of the traits recorded. To date over 250,000 records have been collected for research purposes. A method of capturing BCS measures more easily and remotely would provide a number of benefits for a wider range of stakeholders. Images could be stored for identification purposes and as an audit trail of herd health and could be used in an integrated monitoring system that automatically collects data from a dairy system (Mottram, 1997). An expert management system, running on an on-farm PC using these data, could react proactively to prevent health disorders and adjust management parameters accordingly. These data could then be transferred to a central store for processing into genetic evaluations. This would provide large volumes of objective and low cost data on body energy state changes in dairy cattle.

The use of digital images for information extraction is becoming increasingly possible due to the availability of low cost, high resolution digital cameras and the reduction in price of high performance computers with large disc storage capacity. Its use is being explored in slaughterhouses for carcass grading (Karnuagh et al., 2001) although much of the development of the technology is taking place in the computer games industry.

The capture of BCS information from images must be robust enough to relate to, and be comparable to or better than, information collected by human operators in terms of its relationship to body lipid content. The current available information on the relationship between BCS and body lipid content is based on 20 year old data taken from Friesian type cows (Wright, 1982) and will need to be updated in the future for Holstein type cows. This is particularly important if modern Holstein type cows differ from Friesians in the proportions of fat in different depots.

2.2 Objectives

The first objective was to understand the mechanisms used by skilled operators in assessing cow condition score and to explain differences (if any) between operators in terms of their approach to scoring. This will help to decide what information is required to be extracted from digital images. The second objective was to use information from the first objective to analyse the digital images in order to extract data that relates to the score given to the cow in the image by the scorer. The third objective is to make an assessment of what is required in future research programmes involving remote monitoring of dairy cows to enable research to be targeted and increase the probability of delivering useable outputs.

2.3 Objective 1

2.3.1 *On-farm Condition Score Data*

On the same day, three Field Officers (FO) from HUK assessed all milking cows in the Langhill herd as the cows left the parlour after afternoon milking. These FO's are denoted scorers 1 to 3. The scoring method used by Holstein UK (HUK) is based on that of Lowman et al. (1976) with a 0 to 5 scale but it is adapted to use a 9 point integer scale to be consistent with the other conformation traits assessed in the HUK type classification scheme. The method is also entirely visual and does not involve manual palpation of the cow.

At the same time, the cows were also assessed by two other operators; untrained operator who was unfamiliar with dairy cows (scorer 4) and the operator that had assessed the cows each week for the duration of the long term feeding trial running at Langhill Farm (scorer 5). Both of these operators used the 0 to 5 point scale of Lowman et al. (1976) using quarter point intervals. The experienced operator additionally used manual palpation and the untrained operator relied on visual appraisal only. Data for these two operators were then transformed to a nine-point integer scale using the linear formula suggested by Ferguson (2001) for joint analysis including data from the three HUK Field Officers:

$$BCS_{1to9} = (((BCS_{0to5} * (4/5) + 1) * 2) - 1)$$

This formula is designed to match the end points of the scale and to distribute scores evenly across the range. It can be simplified to:

$$BCS_{1to9} = (BCS_{0to5} * 1.6) + 1)$$

and produces transformed values given in Table 2.1. All operators scored the animals independently and did not confer during the scoring process.

The mean BCS, the number of animals assessed and the standard deviations for each scorer are given in Table 2.2. The difference in numbers assessed is due to animals being missed by one or more scorers and, in the case of scorer 4, three animals were misidentified on the day of scoring and therefore deleted. Correlations between scorers for all cows scored in common are given in Table 2.3.

Table 2.1. Look-up table for body condition score converted from a 0 to 5 scale with quarter point intervals to 1 to 9 integer scale.

Original score	*0.00*	*0.25*	*0.50*	*0.75*	*1.00*	*1.25*	*1.50*	*1.75*	*2.00*	*2.25*	*2.50*	*2.75*	*3.00*	*3.25*	*3.50*	*3.75*	*4.00*	*4.25*	*4.50*	*4.75*	*5.00*
Transformed Score	1.0	1.4	1.8	2.2	2.6	3.0	3.4	3.8	4.2	4.6	5.0	5.4	5.8	6.2	6.6	7.0	7.4	7.6	8.2	8.6	9.0
Rounded Transformed Score	1	1	2	2	3	3	3	4	4	5	5	5	6	6	7	7	7	8	8	9	9

Table 2.2. Mean body condition score (1 to 9 scale) and number of animals for each scorer.

Scorer	*1*	*2*	*3*	*4*	*5*
No. Cows	158	153	159	153	156
Mean BCS	4.53	4.69	4.93	4.38	5.31
SE of mean	0.17	0.16	0.16	0.09	0.05
SD	2.08	1.94	2.01	1.23	0.60

Table 2.3. Correlations between scorers for body condition score (1 to 9 scale) for all cows commonly scored (142 cows).

Scorer	*1*	*2*	*3*	*4*	*5*
1					
2	0.879				
3	0.860	0.918			
4	0.547	0.636	0.616		
5	0.766	0.829	0.792	0.588	

The mean score was significantly different between scorers 4 and 5. The distributions of all scores on a 1 to 9 scale are shown graphically in Figure 2.1 (a to e). The mean for scorer 5 is almost 1 unit higher than that of scorer 4 and about half a unit higher than all of the HUK scorers. Scorer 5's standard deviation is also much lower than all the other scorers and this is visually very evident from the distribution of scores in Figure 2.1e compared to Figures 2.1a to 2.1d.

This raises an important point regarding what information is to be extracted from digital images. It has been assumed that operator 5 can assess body condition very accurately since he has been responsible for scoring the same animals weekly for many years. Therefore it is assumed that the appropriate comparisons to be made regarding accuracy are between operator 5 and the rest. Such an assumption may (or may not) be correct but it does indicate that the BCS scale and method of assessment used at Langhill is substantially different from that adopted by HUK (who were originally trained by Langhill staff). This

difference may be related to the use to which the BCS data is put. HUK officers score in a manner designed to collect useful biological data that can be transformed into genetic evaluations. The scoring of the trait is designed to be near normally distributed across all cows in the country and, on a scale of 1 to 9, have a standard deviation of 1.5. Such a mindset used for scoring linear type traits would appear to be applied to scoring BCS since their scores were well spread out across the full range, with standard deviations all around 2. This would be expected at Langhill since it is a research farm where there are high and low genetic merit cows on high and low concentrate diets even though all cows are almost 100% Holstein. Such variation would generally not be seen on many commercial farms. As such it is therefore surprising that operator 5's scores have lower variation than all other scorers. This is also evident from Table 2.3, where the scores are given transformed to a 0 to 5 scale. Not surprisingly, scorer 4 has the lowest correlation with the rest (Table 2.2) and the HUK field officers (scorers 1 to 3) have the highest correlations between them. Scorer 4 has the lowest correlation with each of the HUK field officers.

Figures 2.1. Distribution of scores by scorer on a 1 to 9 scale.

Figure 2.1a

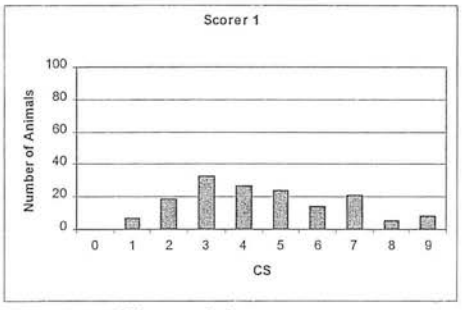


Figure 2.1b

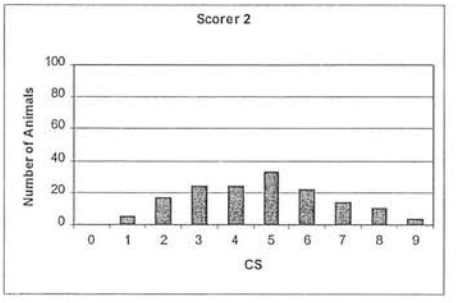


Figure 2.1c

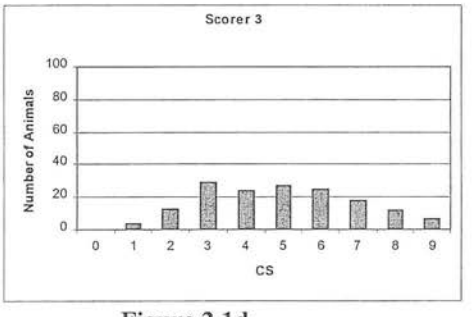


Figure 2.1d

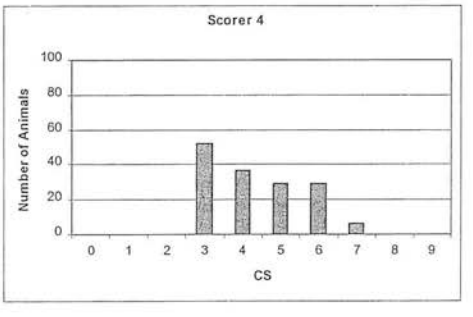
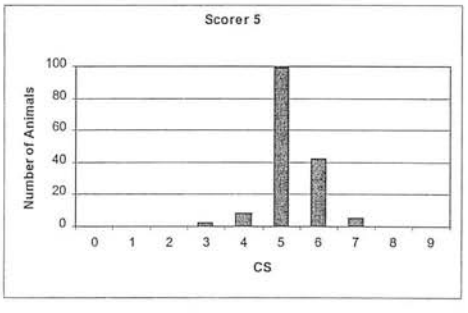


Figure 2.1e



In order to determine if the transformation had introduced any bias, the scores of the HUK field officers were then transformed to a 0 to 5 scale and rounded to quarter point intervals using the linear formula suggested by Ferguson (2001):

$$BCS_{0to5} = (((BCS_{1to9} + 1)/2) - 1) * (5/4)$$

which can be simplified to:

$$BCS_{0to5} = (BCS_{1to9} - 1)/1.6$$

This formula produces transformed values as shown in Table 2.4. Means for each scorer on the actual and transformed 0 to 5 scale are given in Table 2.5 and are presented graphically in Figure 2.2.

Table 2.4. Look-up table for body condition score converted from a 1 to 9 integer scale to 0 to 5 scale with quarter point intervals.

Original Score	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Transformed Score	0.000	0.625	1.250	1.875	2.500	3.125	3.750	4.375	5.000
Rounded Transformed Score	0.00	0.75	1.25	2.00	2.50	3.25	3.75	4.50	5.00

Table 2.5. Mean body condition score (0 to 5 scale) and number of animals for each scorer.

Scorer	*1*	*2*	*3*	*4*	*5*
No. Cows	158	153	159	153	156
Mean BCS	2.20	2.31	2.45	2.11	2.69
SE of mean	0.10	0.10	0.10	0.06	0.03
SD	1.30	1.21	1.26	0.70	0.38

Figure 2.2. Distribution of scores by scorer on a 0 to 5 scale.

Figure 2.2a

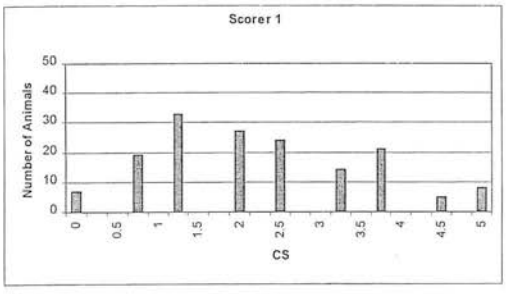


Figure 2.2b

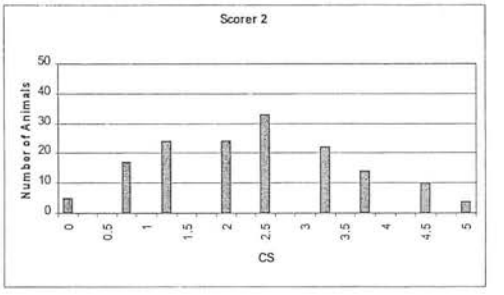


Figure 2.2c

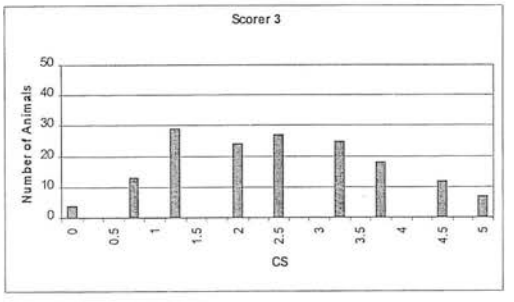


Figure 2.2d

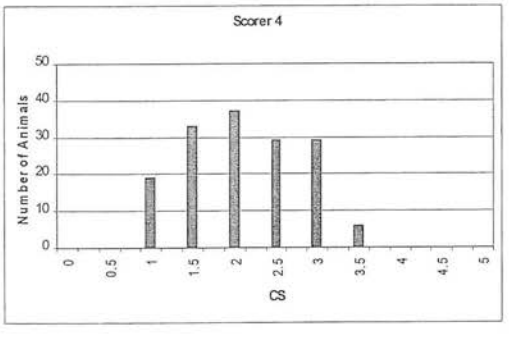
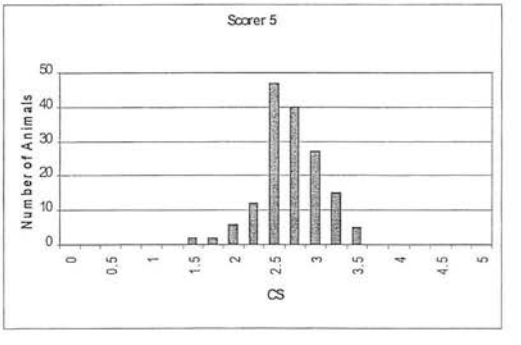


Figure 2.2e



2.3.2 *Scorers height relative to cow*

The type trait Stature is measured by comparing the height of the cows at the withers (across the 'shoulders') to a chalk mark on a wall previously made at fixed heights. The trait can therefore nominally be expressed either as a score of 1 to 9 or a height in centimetres. Table 2.6 gives the height in centimetres for the range of linear scores for Stature. The difference between the height of the scorer and the cow may create a difference in perspective due to the scorer being either taller than the cow and looking down when scoring or shorter than the cow and looking up and not having a clear

view of the forward area of the back of the cow. In this analysis, the difference accounted for a significant proportion of the variance in BCS. However, all three of the HUK Field Officers were noticeably taller than the other two scorers. When added to the regression analysis (see below), it did not alter the accuracy of the fit and the parameter was not significant.

Table 2.6. Conversion table for height and linear type score for Stature.

Score	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Height (cm)	130	133	136	139	142	145	148	151	154

The difference in height between the scorer and cow was calculated for each cow and stored as an additional trait. Means for each scorer are given in Table 2.7. All scorers were taller than the average cow.

Table 2.7. Mean difference in height (cm) between cow and scorer.

Scorer	Mean Difference	Cows
1	-31.5	158
2	-31.6	153
3	-35.5	159
4	-6.6	153
5	-6.5	156

2.3.3 *Use of other traits to improve prediction of BCS*

All linear type traits were tested for a contribution to the prediction of BCS and those found to be significant were subsequently analysed together. These were Angularity (Ang), Chest Width (CW), Body Depth (BD) and Udder Texture (UT). Stepwise regression analyses were then undertaken to determine the proportion of variation in predicted BCS accounted for by these traits. Utilising all traits that had a significant effect produced the following equation with an R^2 value of 48.6:

$$BCS = 4.296 - (Ang * 0.530) + (BD * 0.114) + (CW * 0.324) + (UT * 0.17)$$

Udder texture is subjectively evaluated, is not a shape trait and was therefore removed. Removing it from the regression analysis and therefore leaving only those that might be included in an automatic assessment scheme produced the following formula with a lower R^2 value of 47.9:

$$BCS = 4.764 - (Ang * 0.431) + (BD * 0.099) + (CW * 0.320)$$

Percentage North American Holstein genes of the animal did not account for a significant proportion of the variation in predicted BCS after fitting the linear type traits. This was initially surprising since percentage Holstein is fitted in most UK national evaluations due to its association with production (and by implication to BCS). However, the mean percentage Holstein genes in the Langhill herd is now high (93%) and ranged from 75% to 99% in the cows in this sample. It is likely also that other traits already in the formula, such as Angularity, are associated with percentage Holstein.

These results demonstrate that BCS is associated with a number of body shape traits that might also be included in a future integrated management system. This is consistent with the findings of Pryce et al., (2000) who found a positive correlation between BCS and Body Depth and BCS and Chest Width. Furthermore, Pryce et al. (2002) found that BCS, taken randomly throughout lactation, and 305 day yield were genetically negatively correlated (-0.51) and so milk yield may help in the prediction of BCS in a multi-trait analysis. A future software program running on-farm could utilise all peripheral information, in addition to shape data, to plot a continually evolving curve for each trait of interest including BCS. This would use information on relatives, previous lactation curves (if available) for yield and BCS, sire genetic merit for BCS, dam BCS curve and animal's own production. Such a program would amount to a complete multi-trait animal model running daily and utilising all current information. This would reduce the impact of a spurious BCS estimation from shape data alone and would mimic what may be happening when scorers that have prior knowledge of the animals assign a BCS to that animal.

2.3.4 *Manual condition scoring from photographs*

In order to determine the involvement of visual cues in the scoring process, the HUK Field Officers assessed the whole herd of milking cows for BCS, on a separate occasion, by observing photographs taken from behind while the animal was in the weigh crate, and from the side of the cow whilst the

cow was walking. Enough time had elapsed between occasions (approximately 2 months) to minimise the possibility that the FO remembered the cow from the previous occasion. Each picture was shown at a resolution of 640 by 480 pixels on a Laptop PC screen at the highest resolution of the PC possible (1600 by 1200 pixels) and the FO gave the cow a score based on this image. This was repeated for all cows in both sets of photographs (back pictures and side pictures). The FO was shown pictures of the same cow taken from the back and side at different times, to reduce the possibility that information from one picture was used in deducing the score for the other. The experienced assessor from Langhill (scorer 5) also scored the cows from the same set of photographs, approximately 3 months after they were taken. Scorer 4 did not participate in this exercise.

Results for each scorer are given in Table 2.8 for pictures taken from the side and in Table 2.9 for pictures taken from the rear. Means are the same for pictures taken from the side and rear for scorers 1, 2 and 3 but are significantly different for scorer 5. In this case, scorer 5 gave cows, on average, a higher score when viewing pictures of the cow taken from the side than from the rear. All scorers stated verbally that it is far more difficult to assess BCS from pictures taken from the side because there were few visible features to help deduce the score. This was in part a result of using flash photography, which illuminates the whole side of the cow and therefore reduces shadowing and the contour information that arises from shadows, and in part because there is less contrast in shape of the cow when viewed from the side.

Table 2.8. Mean body condition score (1 to 9 scale) and number of animals for scores given to cows from photographs taken from the side for each scorer.

Scorer	No. Cows	Mean BCS	SE of mean	SD
1	116	5.81	0.19	1.88
2	111	5.89	0.16	1.66
3	116	5.75	0.16	1.69
5	116	6.51	0.10	1.03

For pictures taken from the rear (Table 2.9), the mean score for scorers 1 and 5 was significantly different from scorer 2 but scorers 1 and 5 did not differ from each other or scorer 3. Scorers 1, 2 and 3 all had higher standard deviations than scorer 5 although these are smaller than when scoring the animals live. The standard deviation for scoring from pictures taken from the rear is similar to scores given to the live animal using manual palpation for scorer 5. This would suggest that for visual only scoring, the rear view of the animal is more informative and provides information that is more consistent with that obtained from visual and manual scoring combined.

Table 2.9. Mean condition score (1 to 9 scale) and number of animals for scores given to cows from photographs taken from the rear for each scorer.

Scorer	No. Cows	Mean BCS	SE of mean	SD
1	103	5.77	0.18	1.88
2	104	6.01	0.15	1.63
3	108	5.87	0.18	1.88
5	108	5.63	0.05	0.57

An additional measure was created by calculating the difference between the score given to the animal when the photograph was taken from the rear and when the photograph was taken from the side. Table 2.10 shows the summary statistics for this measure. Scorers 1, 2 and 3 are not significantly different to each other for this measure but all are different to scorer 5. These results would suggest that scorer 5 scores cows on average higher when viewing from the side than from the rear and this is confirmed when considering the mean BCS from Tables 2.4 and 2.5 for scorer 5. Scorers 1 and 3 had maximum individual differences between scores for different views of 7 and 5 respectively. The correlation between side and rear was lower than scorer 3 for both these scorers and was similar to that of scorer 5. However, scorer 5 had no individual differences of above 2.8 and yet still had a low correlation between side view and rear view.

Table 2.10. Correlation between scores and mean, maximum, SD and SE of difference in condition score (1 to 9 scale) for scores given to cows from photographs taken from the side and from the rear for each scorer.

Scorer	No. Cows	Mean difference	SE of mean	Biggest difference	SD	Correlation
1	103	-0.05	0.20	7.0	1.99	0.438
2	104	0.07	0.08	2.0	0.84	0.871
3	108	0.06	0.15	5.0	1.59	0.615
5	108	-0.89	0.09	2.8	0.94	0.434

2.4 Objective 2.

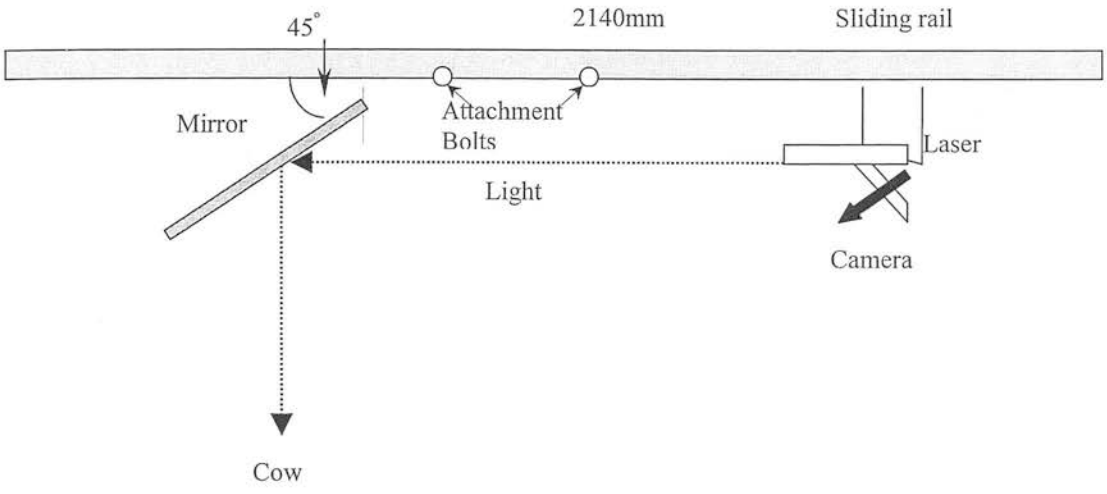
2.4.1 *Automatic condition scoring from digital images*

This objective required the acquisition and analysis of pictures of cows taken from the rear using a commercially available digital camera. All pictures were taken following routine milking once the cow had left the parlour. Pictures had to be taken quickly to prevent a backlog of cows creating a hazard for other cows leaving the parlour. Pictures were either stored in the camera memory when taken at low resolution or, when taken at high resolution, downloaded periodically (each 10 pictures) to a laptop PC connected to the camera via a Universal Serial Bus interface (USB). The camera was activated using a remote control.

2.4.2 *Collection of Digital Photographs*

A rig to hold the camera and structured lighting in a defined and consistent orientation relative to the animal was constructed (Figure 2.3). This rig could be moved horizontally on a slide to accommodate cows of different lengths. It was installed above a weigh crate sited in an exit race from the parlour inside a roofed and partially enclosed small building.

Figure 2.3. Laser light and camera rig.



This building was not contiguous with the parlour. It had a temporary light shield built on the side and black plastic sheeting placed over the roof light to provide a relatively uniform low level of ambient lighting inside the building since the light conditions outside were fluctuating leading to poor photographing conditions. This shroud was not entirely successful in providing a constant ambient lighting environment due to light reflecting off the concrete flooring such that the automatic exposure settings and shutter speed varied. By fixing the exposure, the shutter speed adapted to ambient lighting leading to blurred pictures when the ambient light reduced to too low a level.

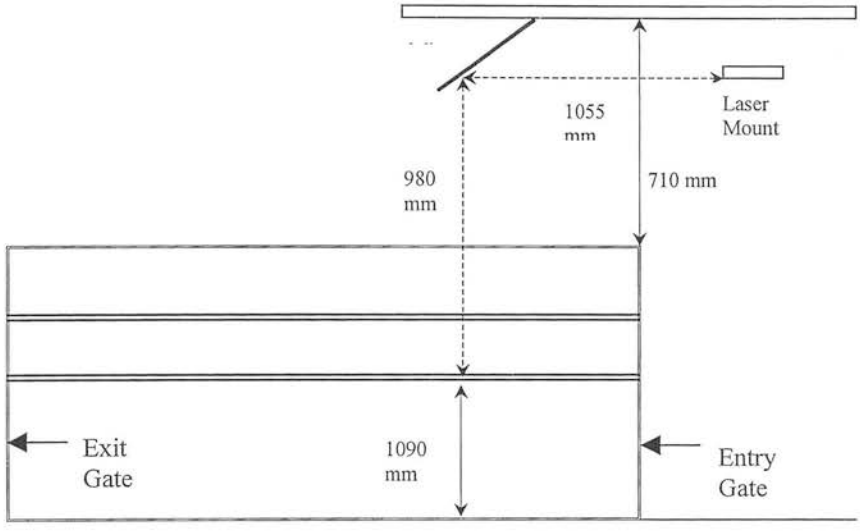
Structured red laser light (wavelength 650nm) was used to create light lines across the area of interest of the cow. It was provided by a 10 milliwatt laser diode module feeding an integral holographic element that split the beam into ten equally-spaced lines. The output array consisted of 10 lines, each line 0.2 degrees divergent orthogonally to the line direction. The line axis divergence was 5 degrees, as was the orthogonal divergence (the cumulative divergence of the lines and "spaces"). A negatively powered "barrel" lens, oriented appropriately, extended the line lengths without affecting the line widths. This lens was mounted appropriately to project line lengths that would accommodate any cow geometry and position within the crate. The laser and lens assembly was mounted horizontally to the rear of the crate and projected froward. A folding mirror re-directed the line array through 90° to project it vertically down on to the back of the cow. This arrangement allowed the light source to be

placed behind and above both the animals and operators to reduce the possibility of the laser light being directly observed at source either by the operators or the cows. The camera was mounted on the same assembly and positioned to be at 45° to the horizontal plane of the cows back. The complete assembly was mounted on a sliding rail that allowed optimum positioning of the light array with respect to the cow, and the overall geometry of the projected light and the camera was therefore maintained. This would simplify any subsequent analysis. The optimum angle between the projected array and the camera is 90° to provide maximum distortion of light. However, the tail head contains contours that orientate vertically and so could not be observed with light at 45° to the cow's back. Camera settings were fixed at each session and all pictures were taken without flash since the laser light lines were rendered unobservable by the flash.

Prior to the start of the experiment, the exact areas of the cow that contained potential information were not known and so previous experience and published results were used to focus on the area of the tail head. In order to test the ability to extract shape information from the images, an aluminium strip was bent into the shape of a cow's pin bone (using the cow as a model) and subsequently compared to the same shape extracted from a picture of the same cow (see section 2.4.6).

As each cow passed into the weigh crate, the camera rig was positioned so that the reflected laser light shone onto the tail head (Figure 2.4) and a picture was taken using a remote control. A set of calibration images was taken at different heights and the camera settings remained the same for all photographs.

Figure 2.4. Laser and photography rig set up with weigh crate



Pictures obtained were variable in quality due to a number of factors. The lighting conditions were changing dramatically and frequently leading to out of focus pictures or pictures where the red light was difficult to see because of high ambient light. However, some pictures could be salvaged using software enhancement filters and an example is shown in Figure 2.5 (before enhancement) and Figure 2.6 (after enhancement). This was achieved by manually altering the brightness and contrast.

Figure 2.5. Original photograph as seen

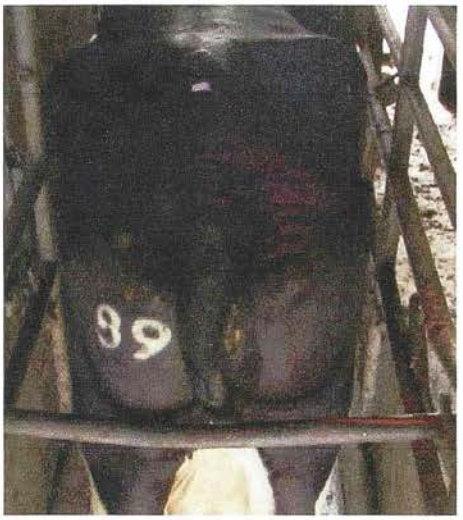
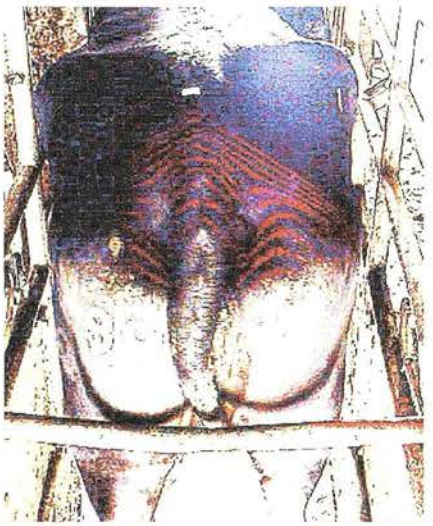


Figure 2.6. Digitally enhanced picture using software

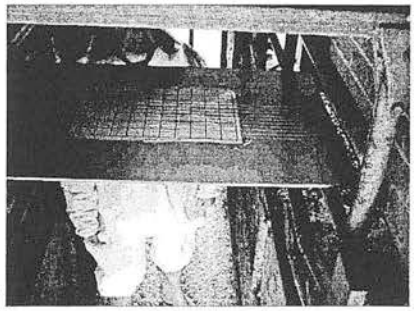


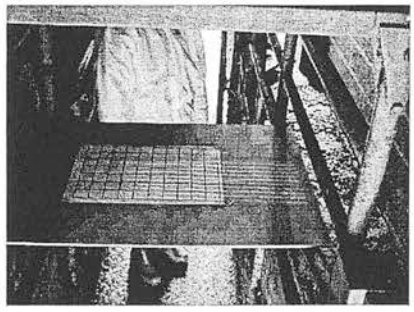
2.4.3 *Camera calibration*

The camera and laser stripes were calibrated using a horizontal grid, which was placed at a different height in each of three images (Tillett, personal communication). Figures. 2.7a – 2.7c show the board at heights of 1160, 1360 and 1570 mm respectively. The 10 laser stripes, projected onto the board, are visible in the images as horizontal lines on the grid. The dimensions of each grid square (column width x row width) were 76.8 by 77.4 mm.

Figure 2.7. Images of laser-striped calibration grid at 3 different heights: (a) 1160mm; (b) 1360mm; (c) 1570; each grid square measured 76.8 x 77.4 mm

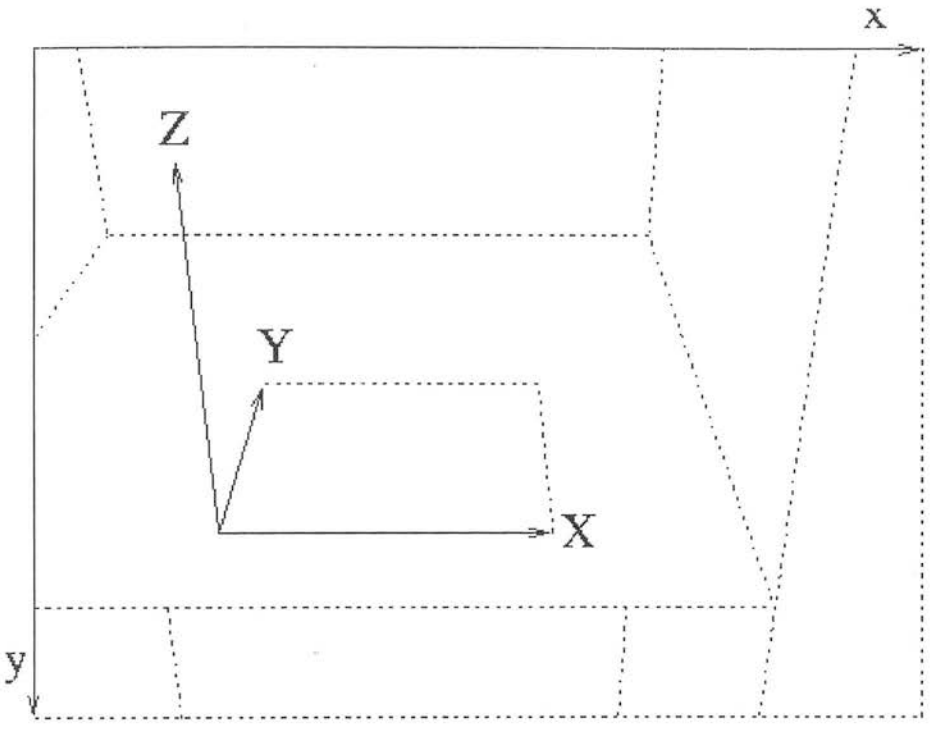
(c) 

(b) 

(a) 

The aim of the calibration was to obtain the world coordinates (X,Y,Z) for a point on a laser stripe, given the screen coordinates (x,y). The directions of these various coordinate axes are shown in Figure 2.8. The X coordinate pointed horizontally left-to-right, the Y coordinate pointed horizontally away from the camera, and the Z coordinate was the world vertical. The x coordinate pointed left-to-right across the image, and the y coordinate pointed vertically down the image.

Figure 2.8. Sketch of calibration image showing directions of world coordinate axes X, Y and Z, and screen coordinate axes x and y



The calibration was performed in two stages. First, the laser stripes were calibrated, giving the world Z coordinate as a function of the screen coordinates. Second, the camera was calibrated to give the world X and Y as functions of x, y and Z. Hence, for a point (x,y) on the *i*th stripe, the world coordinates were given by

$$Z = Z_i(x, y) \qquad \text{...(2.1)}$$

$$X = X(x, y, Z) \qquad \text{...(2.2a)}$$

$$Y = Y(x, y, Z) \qquad \text{...(2.2b)}$$

Where $Z_i(x,y)$ was the calibration function of the *i*th stripe, and X(x,y,Z) and Y(x,y,Z) were the calibration functions of the camera.

The laser stripe calibration was straightforward. For each stripe, the screen coordinates (x,y) of the ends of the stripe were recorded for each calibration height Z, making 6 points in total. A plane was fitted by least-squares through these points, giving

$$Z_i(x,y) = k_1 x + k_2 y + k_3 \qquad ...(2.3)$$

where k_1, k_2 and k_3 were constants. The assumption of linearity was not strictly correct, because each sheet of laser light was a plane in world coordinates, not screen coordinates. However, the fitted planes predicted the Z coordinates with a root mean square (r.m.s.) deviation of 8 mm, so the error was small.

The calibration of the camera was based on the standard equations for a non-distorting perspective camera (Gonzalez & Woods 1992), which were as follows:

$$a_{11}X + a_{12}Y + a_{13}Z - a_{41}xX - a_{42}xY - a_{43}xZ - a_{44}x + a_{14} = 0 \qquad ...(2.4a)$$

$$a_{21}X + a_{22}Y + a_{23}Z - a_{41}yX - a_{42}yY - a_{43}yZ - a_{44}y + a_{24} = 0 \qquad ...(2.4b)$$

where the a_{ij} terms were constants. Rearranging gives the screen coordinates in terms of the world coordinates as:

$$x = \frac{a_{11}X + a_{12}Y + a_{13}Z + a_{14}}{a_{41}X + a_{42}Y + a_{43}Z + a_{44}} \qquad ...(2.5a)$$

$$y = \frac{a_{21}X + a_{22}Y + a_{23}Z + a_{24}}{a_{41}X + a_{42}Y + a_{43}Z + a_{44}} \qquad ...(2.5b)$$

and when Z is known from the laser striping, X and Y can be calculated by solving

$$\begin{bmatrix} a_{11} - a_{41}x & a_{12} - a_{42}x \\ a_{21} - a_{41}y & a_{22} - a_{42}y \end{bmatrix} \begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} -(a_{13} - a_{43}x)Z + a_{44}x - a_{14} \\ -(a_{23} - a_{43}y)Z + a_{44}y - a_{24} \end{bmatrix} \qquad ...(2.6)$$

Clearly, it is possible to choose

$$a_{44} = 1 \qquad \text{...(2.7)}$$

without loss of generality, leaving 11 free parameters to describe the calibration.

Normally at this point it would be a simple matter to find the best fit of this model to the data. However, in this case, there was an additional problem because the calibration grid had been allowed to translate in the horizontal plane when placed at different heights. This introduced an extra set of unknown parameters into the model to account for the (X,Y) translations of the board. With these additional offsets, $X_0(Z)$ and $Y_0(Z)$, Equations 2.5a and 2.5b became

$$x = \frac{a_{11}[X + X_0(Z)] + a_{12}[Y + Y_0(Z)] + a_{13}Z + a_{14}}{a_{41}[X + X_0(Z)] + a_{42}[Y + Y_0(Z)] + a_{43}Z + a_{44}} \qquad \text{...(2.8a)}$$

$$y = \frac{a_{21}[X + X_0(Z)] + a_{22}[Y + Y_0(Z)] + a_{23}Z + a_{24}}{a_{41}[X + X_0(Z)] + a_{42}[Y + Y_0(Z)] + a_{43}Z + a_{44}} \qquad \text{...(2.8b)}$$

where $X_0(1160)$ and $Y_0(1160)$ were defined as zero, and $X_0(1360)$, $Y_0(1360)$, $X_0(1570)$ and $Y_0(1570)$ were four further variable parameters to be determined by model fitting.

This introduced a new problem, in that the direction of the Z axis was no longer constrained to be vertical, because it was not possible to distinguish between the terms which translated the board and those which tilted the Z axis. The solution to this problem was to use the vertical bars of the milking crate to constrain the vertical direction. The vanishing point (x_v,y_v) of the vertical bars was easily determined from any of the images in Figures 2.7a-2.7c. In mathematical terms, the vanishing point is the point in image coordinates at which Z tends to infinity, which from Equations 2.8a and 2.8b is given by

$$x_v = a_{13}/a_{43} \qquad \text{...(2.9a)}$$

$$y_v = a_{23}/a_{43} \qquad \text{...(2.9b)}$$

Substituting for a_{13} and a_{23} in Equations 8a and 8b leads to

$$x = \frac{a_{11}[X + X_0(Z)] + a_{12}[Y + Y_0(Z)] + a_{43}x_v Z + a_{14}}{a_{41}[X + X_0(Z)] + a_{42}[Y + Y_0(Z)] + a_{43}Z + a_{44}} \qquad \text{...(2.10a)}$$

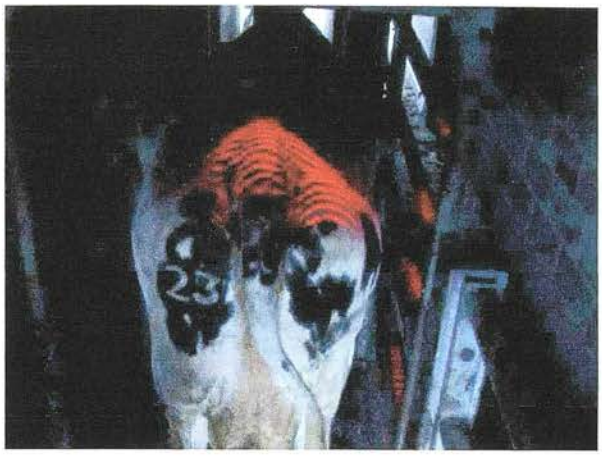
$$y = \frac{a_{21}[X + X_0(Z)] + a_{22}[Y + Y_0(Z)] + a_{43}y_v Z + a_{24}}{a_{41}[X + X_0(Z)] + a_{42}[Y + Y_0(Z)] + a_{43}Z + a_{44}} \qquad \text{...(2.10b)}$$

The 13 free parameters of Equations 2.10a and 2.10b (including the variable offset terms) were optimised to obtain the best fit of the predicted x and y values to the actual image coordinates in Figures 2.7a-2.7c. Once the model was fitted, the world coordinates of any image point on a laser stripe could be calculated by solution of Equation 2.6.

2.4.4 *Extraction of shape data from images*

The extraction of shape data from the laser-striped cows consisted of two steps: (1) manual extraction of points on the laser stripes; and (2) extraction of shape parameters by curve fitting. Figure 2.9 shows a typical image of a cow in which the 10 laser stripes have been projected onto the area surrounding the pin bone. In all cases, the stripes extended across the tail head and the right buttock, but not the left buttock. This was due to the laser lights not being long enough to cover the whole back of the cow and it was assumed that the cow's back is symmetrical.

Figure 2.9. Typical image of laser-striped cow



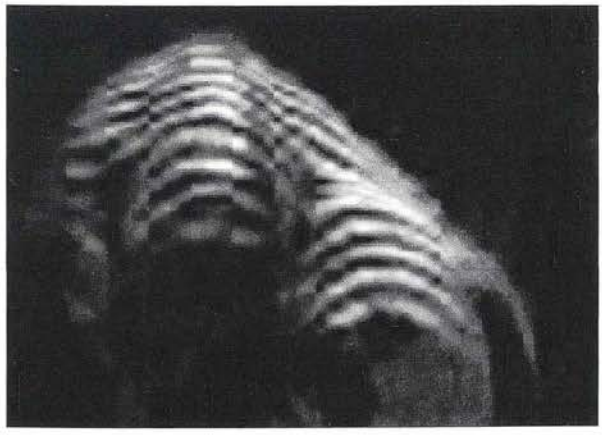
2.4.5 *Manual extraction of stripe data*

For each cow image, an initial enhancement of the image was performed, for the benefit of the human eye. Figure 2.10 shows the result of enhancing the Figure 2.9 image, in which the region of interest over the striped area was expanded by a factor of four, and the contrast was increased by part-subtraction of the blue colour channel from the red, according to the *ad-hoc* formula

$$p = (3R - B)/3 \qquad \text{...(2.11)}$$

where R and B were the values in the red and blue channels respectively, and p was the enhanced pixel value. After the colour transformation, the grey levels were stretched into the range 0-255 for maximum contrast.

Figure 2.10. Enhanced image of laser stripes on cow



It can be seen in Figure 2.9 that the images were visually of poor quality. This was due to several factors: the extremes of lighting contrast in the crate which caused the automatic gain of the camera to

vary wildly; the very low reflectance of black patches on the cow's coat (not present in Figure 2.9); and the loss of data due to the use of JPEG image compression in the camera.

After image enhancement, points on the laser stripes were marked in software by clicking with a mouse. This was performed for as many stripes as possible, although it was rare for all 10 stripes to be visible on a given cow. In order to determine the positions of the points relative to the cow, the position of the tail head was indicated in the image by manually straddling it with two straight lines. The relative position of the points in the head-to-tail direction was much more difficult, because of the lack of clear landmarks; an estimate was made of which stripe passed over the pin bone, but the position of the bone was not always obvious.

2.4.6 *Curve fitting and extraction of shape parameters*

Each of the manually collected points was compared to the position of the tail head, and was labelled as being within the tail region, or to the left or right of it. The image coordinates (x,y) were transformed into world coordinates (X,Y,Z) by Equations 2.3 and 2.6.

It would seem reasonable to expect cows with poor condition scores to be more "bony" in shape, have less cover over skeletal structures thereby revealing their shape, and that this might be determined by measuring the curvature of the tail head or the buttock. The simplest method of measuring curvature was to fit a quadratic through the data

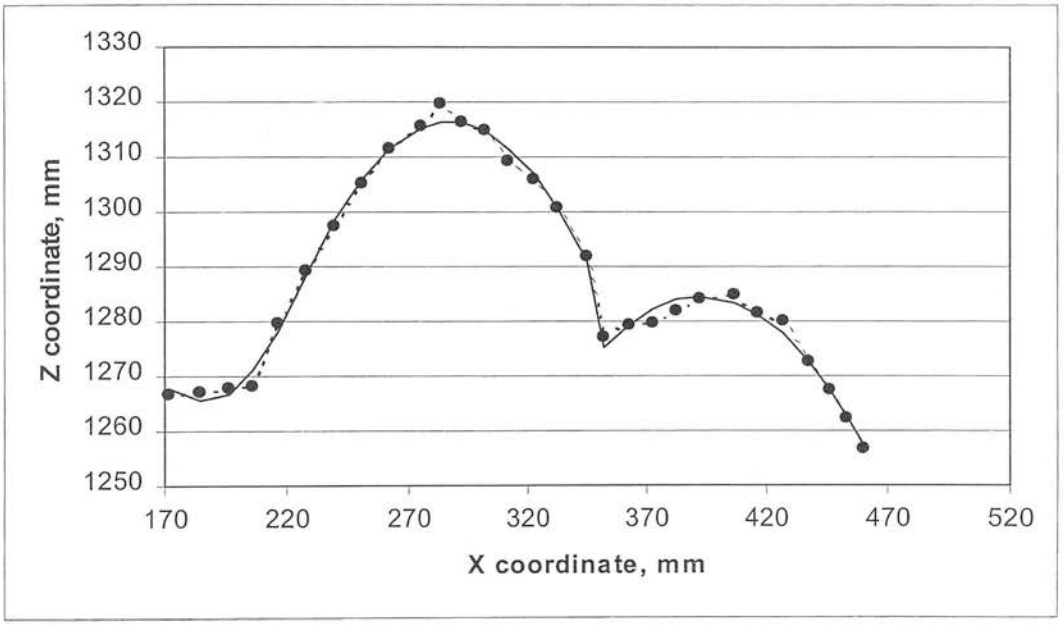
$$Z = c(X - X_0)^2 + Z_0 \qquad \text{...(2.12)}$$

where (X_0,Z_0) was the position of the peak, and c was the curvature. The stripes were assumed to be straight in the (X,Y) plane, so the quadratics were fitted as Z against X, with the Y coordinate being ignored.

For each stripe, two quadratic curves were fitted through the data: one through the points in the tail head region, and one through the points on the right buttock. In effect, this assumed that the shape of

the cow, from left to right, could be approximated by three quadratic humps: one for each buttock and one for the tail head. Figure 2.11 shows a typical fit to the data across the pin bone.

Figure 2.11. Typical fit of model to cow shape (tail head and right buttock) across the pin bone: broken line, laser stripe data; solid line, fitted quadratics



It was not possible to measure any shape parameters other than these two curvatures. It would have been of interest to measure the depth of the dip between the tail and the pin bone, but the laser stripes were particularly difficult to follow in this region, because of the rapid change in height. No attempt was made to extract shape changes from stripe to stripe, that is, in the head-to-tail direction, because the data were too incomplete.

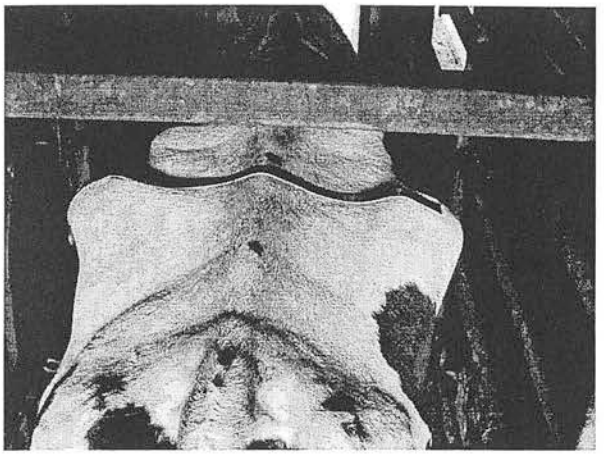
A data cleansing step was performed to remove all the stripes for which the quadratic fit was poor. All stripes which were based on fewer than 5 data points, or which produced a poor r.m.s. fit to the data, were rejected. A threshold was also applied to the curvature itself, since a result which was outside the normal range would indicate a failure of the fitting process. For each cow, there were several stripes, and hence several curvature measurements. For comparison with the condition score,

it was necessary to form an aggregate curvature over all the stripes. Various aggregation methods were used: the minimum, mean, median and maximum, as well as the manual choice of the stripe corresponding to the pin bone. The aggregate curvatures of the tail head and the right buttock were compared by cross-correlation with condition scores and visual assessments (see Section 2.4.7)

2.4.7 *Verification of shape extraction*

In order to demonstrate that the shape extracted from the laser stripe data was correct, an aluminium strip was pressed against a cow's back, producing a metal record of the shape across the hook bones, as shown in Figure 2.12. The shape of the strip was digitised manually using graph paper. A laser stripe was projected in the same place on the cow, and the (X,Y,Z) coordinates of the stripe were extracted from the image as described in Section 2.4.6. The coordinates extracted from the image were compared with those obtained from the metal strip.

Figure 2.12. Image of aluminium strip being used to record cow shape.

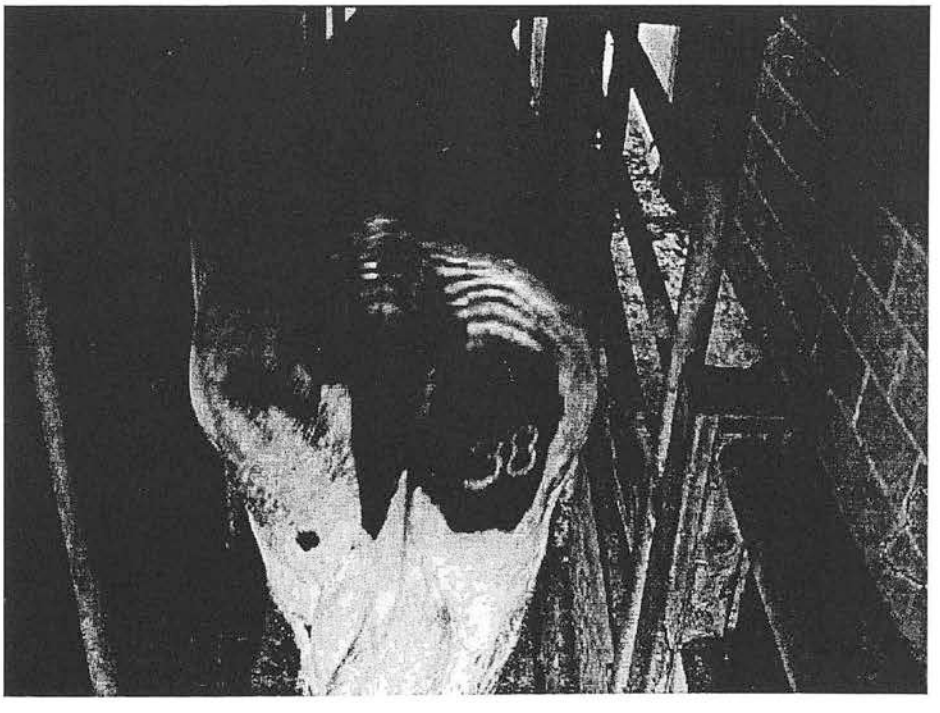


2.4.8 *Condition scoring from digital images*

The condition score given to the cow by the skilled operator at Langhill (scorer 5) did not always seem to correspond to that suggested to the untrained eye from the appearance of the cow in the laser-striped image. For example, the two cows shown in Figs. 13a and 13b were of widely differing appearance, but had been given the same condition score of 2.5. This suggested that the images might not contain all the information used by scorer 5 for condition scoring. To test this, the cow images, for which shape data could be extracted, were scored visually by three independent assessors denoted V1, V2 and V3, who ranked the appearance of the cows on an arbitrary 10-point scale. The first assessor had no experience of condition scoring (V1), the second (V2) had had some experience (although not with cows) and the third (V3) was a cow-condition expert used to assess cows at Langhill (scorer 5). Correlation coefficients were calculated between the visual assessments and the condition score, and also between the three assessors themselves. The condition score and visual scores were compared with the shape parameters - the curvatures of the tail head and the buttock - extracted from the laser stripes (see Section 2.4.6)

Figure 2.13a. Image of cow with poor visual appearance, but given average condition score.

Figure 2.13b. Image of cow with good visual appearance, but same condition score as cow in Figure 2.13a.



2.4.9 *October 2001 images*

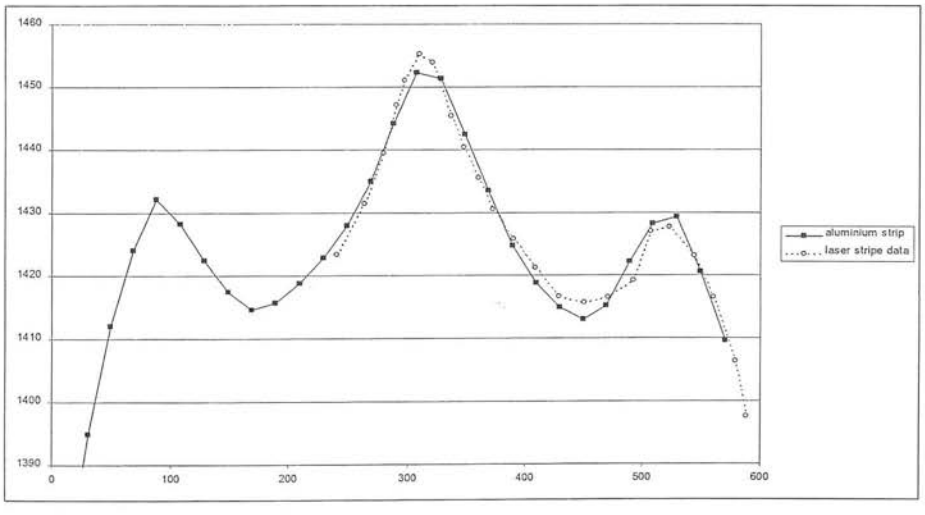
A set of images, one of which has been shown in Figure 2.9, was captured in October 2001. A total of 36 (out of 189) images were of suitable quality for the stripes to be manually extracted. The images were processed as described in sections 2.3 and 2.4, to extract the world coordinates of the stripes and the curvatures of the tail head and the right buttock. The correlation coefficients were measured between the curvatures and the condition scores.

2.5 Results of condition scoring from digital images

2.5.1 *Comparison with aluminium strip.*

Figure 2.14 shows the shape of the Figure 2.13 cow, as extracted from the image and the aluminium strip, plotted as Z against X. The vertical scale in Figure 2.14 is exaggerated. The relative translation and rotation of the two sets of coordinates were unknown, so the set digitised from the strip was allowed to translate and rotate for the best fit. The r.m.s. fit of the image-derived coordinates to the strip was +/- 2.1 mm, with a maximum deviation of +/- 4.4 mm.

Figure 2.14. Comparison of coordinates extracted from laser stripe data with shape measured from aluminium strip.

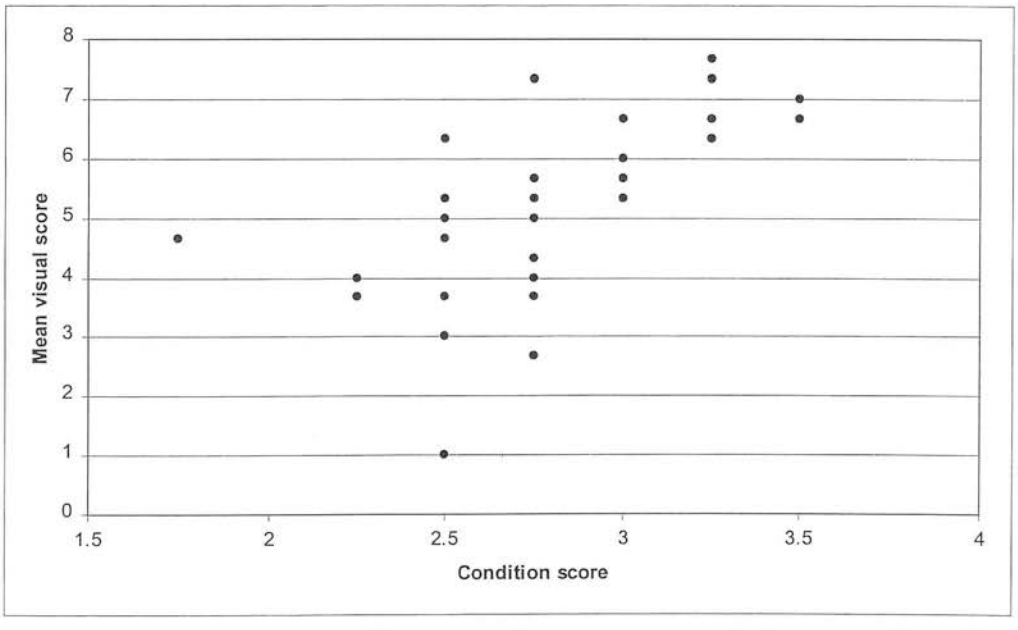


2.5.2 *Results from October 2001 images*

Thirty six cow images were of suitable quality for the laser stripes to be extracted. 224 stripes were extracted from these, an average of 6 stripes per cow. In the data cleansing step, stripes based on fewer than 5 data points were removed. The r.m.s. fit of the quadratic curve was examined, and a threshold of +/- 3.6 mm was found to give a good subjective separation between the "good" and the "poor" fits. Stripes with a worse r.m.s. fit than this were rejected. Finally, a curvature threshold was applied. The normal range for both the tail head and the buttock was found to be less than (i.e. more curved than) -0.005 mm^{-1}. Curvature results which were flatter than this were assumed to be failures of the fitting process, and were rejected. After data cleansing, 142 stripes remained over the tail head and 80 over the right buttock. Nineteen cows had well-fitted stripes over the pin bone itself.

Visual assessments were made of the cow condition in each of these images, as described in Section 2.4.8. Figure 2.15 shows a plot of the mean visual score against condition score.

Figure 2.15. Scatter plot of mean visual assessment scores against condition scores



It can be seen from Figure 2.15 that, for the pictures that shape data could be extracted, most of the condition scores were in a small range between 2.25 and 3.25, making any correlation coefficients

highly dependent on the small number of data points at the extremes, such as the single point at condition score 1.75. Future work will need to ensure that the data set contains a wider range of condition scores.

Table 2.11 shows the correlation coefficients of the visual assessments against the condition scores, and against each other. It can be seen that the correlation between the visual assessment and the condition score varied from about 40 to 50%, rising to 62% when the mean of the three visual assessors was used. The correlation of scores between the three individuals themselves was not strong, particularly between assessor V1, who had no experience of condition scoring, and the others. The results confirmed the initial suggestion (see Section 2.4.7) that not all of the condition score factors were visible in the images.

Table 2.11. Cross correlation coefficients for all cows: comparison between condition scores (CS) and scores derived from human visual assessments of images (V1, V2, V3). Vm is the mean of V1, V2 and V3.

	CS	V1	V2	V3
CS	1.0	0.41	0.54	0.46
V1	0.41	1.0	0.19	0.25
V2	0.54	0.19	1.0	0.62
V3	0.46	0.25	0.62	1.0
Vm	0.62			

Tables 2.12a and 2.12b show the correlation coefficients between the condition scores and the curvatures of the tail head and the buttock. These were the aggregate curvatures of each cow, determined by the minimum, mean, median and maximum of the curvature of all the stripes, or by manually selecting the pin-bone stripe (see Section 2.4.4).

Table 2.12a. Cross correlation coefficients over all cows: condition scores (CS) and visual assessments (V1 to V3 and mean (Vm)) against curvature of tail head. Min, mean, median and max were the methods by which the aggregate curvature was calculated for each cow. Pin was the curvature of the single stripe which was manually selected as being the closest to the pin bone.

	min	mean	Median	max	pin
CS	0.40	0.55	0.56	0.50	0.58
V1	0.34	0.31	0.31	0.11	0.25
V2	0.35	0.42	0.46	0.29	0.18
V3	0.34	0.56	0.54	0.59	0.19
Vm	0.44	0.56	0.57	0.43	0.26

Table 2.12b. Cross correlation coefficients over all cows: condition scores (CS) and visual assessments (V1 to V3 and mean (Vm)) against curvature of right buttock. Min, mean, median and max were the methods by which the aggregate curvature was calculated for each cow. Pin was the curvature of the single stripe which was manually selected as being the closest to the pin bone.

	min	mean	Median	max	pin
CS	0.27	0.40	0.40	0.36	0.52
V1	0.41	0.50	0.47	0.45	0.50
V2	0.29	0.38	0.42	0.27	0.46
V3	0.38	0.54	0.54	0.55	0.61
Vm	0.46	0.60	0.61	0.53	0.68

The curvatures of the tail head and the buttock were correlated with the condition scores and the visual assessments strongly enough to show the correlation between shape and condition, but not strongly enough to reliably predict the condition score from the shape. For the tail head (see Table 2.12a), the correlations obtained using the mean, median or pin bone were similar at 55 to 58%, probably because the curvature did not vary much down the length of the cow. The mean also had a 56% correlation with the visual assessments, so the mean appeared to be the most reliable method. For the buttock (see Table 2.12b) the stripe over the pin bone gave the best correlation to the condition score (52%) and the visual assessment (68%). This was not surprising as this curvature varied considerably along the cow, reaching a maximum in the area of the pin bone. It was interesting to note, however, that the correlation was poor when the maximum curvature itself was used, probably because this aggregation method was sensitive to noise. Figure 2.16 shows the mean tail head curvature plotted against the condition score (CS). Figure 2.17 shows the pin bone curvature of the right buttock, plotted against the condition score. Figure 2.18 shows the pin bone curvature of the right buttock, plotted against the mean visual assessment (Vm). Adding the curvatures of the tail head and the buttock together did not produce a variable with significantly better correlation with condition score, indicating that the two curvatures were not independent of each other.

Figure 2.16. Scatter plot of mean tail head curvature against condition score, correlation coefficient 55%

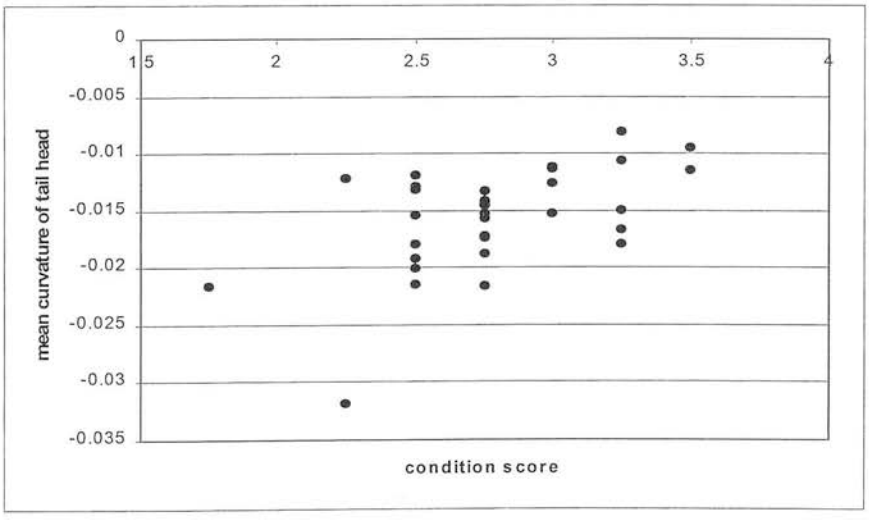


Figure 2.17. Scatter plot of curvature of right buttock, as measured across pin bone, against condition score, correlation coefficient 52%

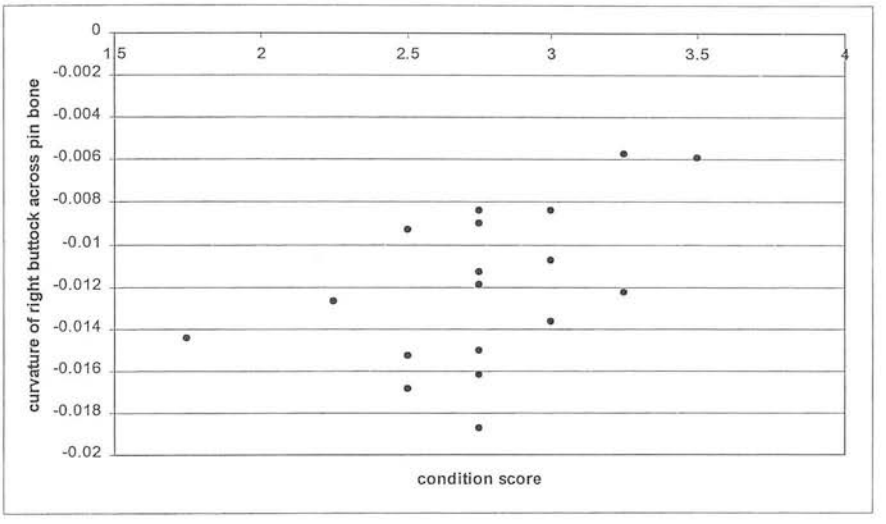
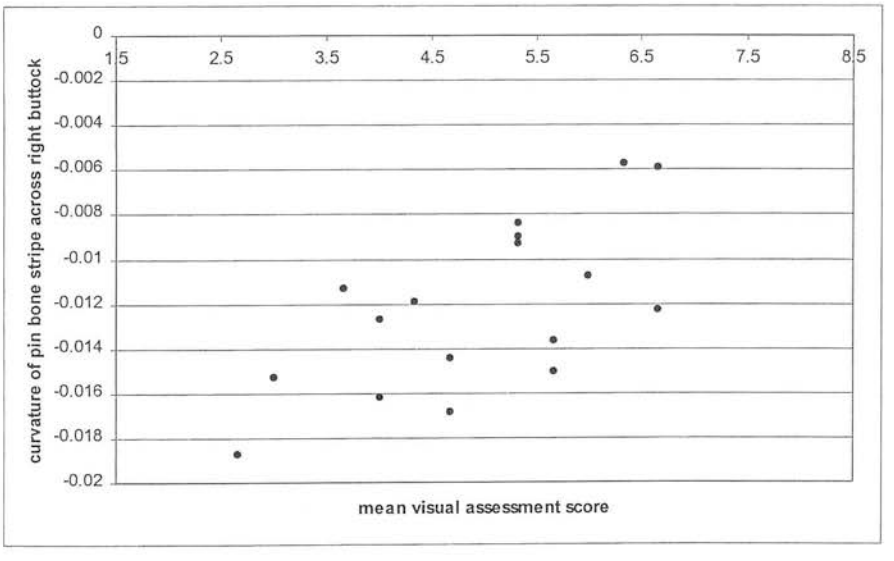


Figure 2.18. Scatter plot of curvature of right buttock, as measured across pin bone, against mean visual assessment score, correlation coefficient 68%



It is interesting to note from Tables 2.12a and 2.12b that the curvatures obtained from the laser stripes were more strongly correlated with the visual assessments than with the condition score given by scorer 5. Perhaps this should not be surprising, since condition scoring includes non-visual factors

such as touch, and may also have been subject to some a priori bias on the part of the assessor as to the expected shape of a given cow.

2.5.3 *Conclusions for automatic condition scoring from digital images*

Measurements of cow shape were measured by laser striping across the tail head and buttocks. Comparison with the shape, as recorded using an aluminium strip, showed that the r.m.s. accuracy was +/- 2.1 mm in the vertical direction. Two measures of shape were tested for their correlation with condition score. The curvatures of the tail head and right buttock were selected because they were thought to be measures of the "boniness" of the animal.

2.6 DISCUSSION

The same operator has been responsible for condition scoring at Langhill for approximately 20 years and he has an in depth knowledge of all the cows identities, their history and ancestry, current health and productive status. Most importantly, the operator is familiar with the cows last BCS and it is possible (or even likely) that this collateral information subconsciously influences the score given at any one session. This may, in part, be an explanation for the lower variation for BCS for this operator than the others (Table 2.3) and the lower correlation with the other scorers (Table 2.4). This suggests that the BCS given by this operator contains more information than just a manual palpation and visual appraisal of BCS using one site or that the operator is unwittingly making adjustments for other factors. Such multi-factorial assessment of BCS would be difficult to emulate using digital image processing since the visual cues are difficult to define and may be different for different fat classes of animals e.g. thin or fat. However, it does provide a model upon which an expert system embedded within software could operate. At the start of the trial, it was assumed that the Langhill operator would be the most accurate due to experience and regular practice. The main objective was to emulate this operator's activity. This assumption must be revised since the same operator has been using the same system for many years on cows that have changed extensively from typical Friesian types to almost pure Holstein types. The body fat content and distribution within animal has not been studied in modern Holstein type dairy cows and it is possible that the system of condition scoring needs to be

revised or at least calibrated before it is used more widely in management or auditing systems with modern dairy cows.

Discussion with the HUK Field Officers reveals that even though they were trained by Langhill operators to score animals in one place (over the loin area), on occasion when that proves difficult to do they also use visual cues from additional sites. This appears to be particularly so when viewing the animal from behind. In this instance they look at both the tail-head and the loin area by looking over the top of the tail-head towards the head of the cow. This does not generally occur explicitly when looking from the side since many of the cues are visible from the side. Given that the pictures that they scored from were taken from above and behind, the forward part of the cow was also visible and it is difficult to know from this work whether they used that information at the same time to arrive at a BCS.

Body energy state, as indicated by BCS and its change, is potentially a very valuable trait for both management and selection purposes. It not only indicates current nutritional status but can be used in conjunction with other traits to predict fertility (Pryce et al., 2000). Lower fertility is a major cost to the UK dairy industry both through direct routes such as increased management and semen costs and through opportunity costs arising from high producing cows being unable to provide replacements. Research to develop automated and integrated monitoring tools will be expensive and requires targeting to the most promising technologies that are achievable. However, given the difficulty in emulating visual cues from digital images, perhaps the more realistic objective to pursue would be to find parameters of a shape (or combination of shapes) that is related to body fatness itself and then to relate that shape parameter to BCS. In this project, the work set out to predict BCS which is itself a predictor of body fat content. The system of determining BCS (Lowman et al., 1976) was developed for visual appraisal of beef cows and exploits the human eye's ability to assimilate a large number of interacting and subtle cues. Expecting software to be able to emulate that process might be unrealistic in the short term but defining a new system especially for digital image capture may make body energy assessment from digital images more feasible in future. This might involve digitally captured shape data from more than one site in conjunction with historical data for animals already in the herd

or standard curves for new animals combined with information from relatives. Reducing the impact of the shape data alone may allow more opportunities for continued research into extracting shape data whilst allowing for the best use to be made of all available data.

The work presented here fell into two main categories, the first associated with the process of condition scoring and the second with the process of taking digital images and extracting shape information from digital images. These might broadly be categorised as a biological question and an engineering question. The resultant benefit arises from the relevance of an engineering solution to a biological need. The future research priorities in this area are associated with biological and engineering questions.

The total body fat in a dairy cow is assumed to be related to BCS based on work utilising distinctly different genotypes (Friesian) than those (Holstein) available today. Therefore the success of the engineering solution is measured against the ability of shape information to mimic condition scoring in Holstein cattle. This may not be a relevant comparison since body fat distribution could have changed as a result of changing genotypes or selection objectives.

The visual cues used in assessing BCS are varied and subject to effects that can be subtle e.g. hydration of the cow. Experienced operators use a number of visual cues plus, apparently, collateral information and knowledge of the recent history of the cow. This implies that an automatic system of assessing some measure of body fat will have to use as much information as possible aside from the shape of the animal. What those elements of information are needs to be identified.

The small number of data points in the set, particularly the lack of cows with extreme condition scores, made it difficult to draw firm conclusions on the relationship between aspects of shape and BCS. Further work needs to ensure that more examples of extreme condition scores are included in the data set and to improve the quality of the images. This would increase the number of cows which it was possible to measure, enable more reliable conclusions about the visual assessments to be drawn, and allow other measures of shape to be extracted. Given better images, it would be interesting to

produce a complete 2-D model of the cow shape, modelling the shape changes between stripes, as well as across the cow. This would be useful in locating landmarks such as the pin bone along the axial direction, as well as yielding more shape parameters for predicting condition scores. It would be of interest to extract similar measures of shape in the area of the hook bones, which might produce a different correlation with the condition score, and would be easier to locate than the pin bones in an automatic system.

An integrated dairy monitoring and management system would enable more precise management of day to day use of inputs in a dairy enterprise. This would be beneficial from an environmental aspect since remote monitoring of cow outputs (milk, slurry, methane etc) could provide data currently either unavailable or extremely difficult to obtain. The use of images in such a system could bring additional benefits such as improved health and welfare since fresh images of the physical appearance of cows would be available at the time managers are making decisions. The equipment required to assimilate these data is rapidly reducing in price and size whilst increasing in power. It is easy to envisage a computerised system capturing still images via digital cameras at strategic points such as the parlour exit race and real time pictures via a web cam for real time monitoring of activity such as oestrus behaviour.

2.7 CONCLUSIONS

Shape information relating to BCS can be extracted from digital images of dairy cows with limited accuracy. Not all of the information contained in BCS is available in digital images alone but some can additionally be obtained from normal farm recording systems. Additional information on body fat content might be derived from images taken at more than one place on the cow. Further research into automated body fat assessment from digital images is warranted with a view to constructing an integrated dairy cow monitoring system in order to improve cow welfare and reduce the environmental impact of dairy production systems.

CHAPTER 3

Genetic Evaluation of Dairy Bulls For Energy Balance Traits Using Random Regression

3.1 SUMMARY

Current selection objectives for dairy cattle breeding may be favouring cows that are genetically predisposed to mobilise body tissue. This may have consequences for fertility since cows may resume reproductive activity only once the nadir of negative energy balance (NEB) has passed. In this study, I repeatedly measured feed intake, liveweight, milk yield and condition score of Holstein cattle in their first lactation. They were fed either a high concentrate or low concentrate diet and were either selected or control animals for genetic merit for kg milk fat plus milk protein. Orthogonal polynomials were used to model each trait over time and random regression techniques allowed curves to vary between animals at both the genetic and the permanent environmental levels. Breeding values for bulls were calculated for each trait for each day of lactation. Estimates of genetic merit for energy balance were calculated from combined breeding values for either 1) liveweight and body condition score changes, or 2) feed intake and milk yield output.

When estimated from daily fluxes of energy calculated from feed intake and milk output, the average genetic merit of bulls for energy balance was approximately –15MJ/day in early lactation. It became positive at about day 40 and rose to +18MJ/day at approximately day 150. When estimated from body energy state changes the NEB in early lactation was also –15MJ/day. It became positive at about day 80 and then rose to a peak of +10MJ/day. The difference between the two methods may arise either because of the contribution of feed wastage to intake measures or through inadequate predictions of body lipid from equations using liveweight and condition score or a combination of both. Body energy mobilised in early lactation was not fully recovered until day 200 of lactation. The results suggest that energy balance may be estimated from changes in body energy state that can be calculated from body weight and condition score. Since body weight can be predicted from linear type measures, it may be possible to calculate breeding values for energy balance from national evaluations for production and type. Energy balance may be more suitable as a breeding objective than persistency.

3.2 INTRODUCTION

The term 'negative energy balance' (NEB) in dairy cows is commonly used when describing the period in early lactation when the energy available to the cow from food intake is lower than that of the energy used by the cow for milk output, maintenance and activity. The cow makes good the deficit by mobilising body tissue. Current selection objectives may be favouring cows that are genetically predisposed to mobilise body tissue. It has been estimated that without food intake (FI) in the breeding goal, each increment in genetic merit for production is resulting in only a 48% concomitant rise in food intake for cows (Veerkamp *et al.*, 1995). This may have consequences for fertility since cows appear to resume reproductive activity only after the nadir of NEB has passed (Butler and Smith 1989, Beam and Butler 1998, Veerkamp *et al.*, 2000). Fertility, measured as average days to first *post partum* oestrus, has been declining at approximately 0.5% per year in USA and approximately 1% in the UK (Royal *et al.*, 1999). A delay in commencement of luteal activity in cows that are in NEB has been reported in a number of studies (De Vries *et al.*, 1999, Veerkamp *et al.*, 2000). The extent and duration of NEB may be a causal factor in the greater decrease in fertility observed in dairy cows in the UK compared to those in the USA. A component of that NEB will be due to management since the UK cow population is derived principally from North American genetic material and there are phenotypic differences in fertility decline between the two genetically similar populations.

The objective of many dairy management systems is to minimise the extent and duration of NEB because of its presumed effect on fertility (Pryce *et al.*, 1999). NEB has also been reported as an indicator of metabolic load or stress in dairy cows (Nielson, 1999). As such, extreme NEB may be considered generally undesirable, as it is a precursor to health and fertility problems and results in metabolic stress. Body condition score (BCS) is a management technique used routinely to appraise the body fat reserves in cattle (Lowman *et al.*, 1976). Changes in BCS over time are routinely used as a barometer of nutritional status of dairy cattle. Although heifers were classified only once during their lactation, Jones *et al.*, (1999) used random regression techniques to produce breeding values for bulls for BCS at all stages of lactation of daughters. Heritabilities ranged from 0.20 to 0.28 throughout lactation. They demonstrated that the genetic control of BCS varied throughout lactation and that there was variation between progeny groups. Their results suggest that selection indexes including bull BCS

profiles based on field measurements on daughters are possible. Genetic analysis of energy balance would allow for the estimation of breeding values for bulls. Random regression is a useful technique for analysing traits with repeated measures during the same lactation (Hill and Brotherstone, 1999) in order to construct a profile for that trait. These repeated measures need not be made on the same animal, e.g. they can be from daughters of a particular bull scored at various stages of lactation. Random regression models account for the difference between animals in the curve for the trait being evaluated (Schaeffer and Dekkers, 1994). An average curve of a known shape, that may be expected to reflect the underlying biological processes related to the trait, is fitted as a fixed regression applicable to all animals in a particular group. Deviations from this average curve are modelled for each animal, using polynomials or parametric curves. Inclusion of the relationship between animals allows these deviations to be partitioned into a genetic component, a component due to the permanent environment of that particular animal and a random measurement error. By modelling permanent environmental effects over time, I avoid the assumption of equal environmental correlations between all pairs of records. The analysis yields two sets of curve coefficients for each animal, allowing estimates to be made of its genetic merit and permanent environment at all points along the trajectory.

In this study, it is the shape of the energy balance profile that is of interest. It is important when we consider that energy balance is the consequence of changes in a number of energy sinks. (1) The energy available from feed ingested minus energy required for production, maintenance and activity or 2) the energy contributed by, or used for, changes in the weights of body protein and lipid. In addition, at least in this study, traits influencing or influenced by these energy sinks are measured at different times of the lactation and with different frequencies. The genetic evaluation of each of these traits would allow the estimation of a genetic evaluation for energy balance for animals used in this study using two methods of calculation. This would then enable the calibration of energy balance calculated from body state changes against energy balance calculated from estimates of daily feed intake and milk output, which could be more accurate. Using additional field data such as condition score and type traits to predict liveweight (LWT) (Koenen and Groen 1998) would allow the extension of one of these methods of calculation to produce national evaluations for energy balance profiles of bulls.

At the phenotypic level, the estimation of energy balance is subject to significant error. The calculation of energy intake is a product of FI measurement, which will include any physical wastage, and the estimation of feed energy content. The estimation of the feed energy content usually relies partly on published values for feed constituents (ARC 1993) and partly on chemical analysis and its interpretation. Energy balance, calculated from estimates of changes in the weights of body lipid and body protein, relies on the predictions of these quantities from LWT and BCS measurements. De Vries *et al.*, (1999) estimated energy balance as the difference between energy requirements (calculated from milk output plus maintenance) and energy consumed. Different traits have been reported as predictors of energy balance such as LWT (Veerkamp and Koenen., 1999) and milk fat percentage change (Veerkamp *et al.*, 2000).

The objectives of this study were: 1) to produce genetic evaluations for sires using random regression techniques and restricted maximum likelihood (REML) for traits contributing to energy balance in first parity dairy cows from the Langhill Dairy Cattle Research Centre; 2) to combine those breeding values into an overall energy balance evaluation for bulls.

3.3 MATERIAL AND METHODS

3.3.1 Data

Data were extracted in July 1998 for 298 heifers from the database of Langhill records collected since 1990. This database includes extensive records of milk production and composition, LWT, BCS and FI for two lines of cows. The lines are selected either for kg fat plus protein (S) or control cows (C) selected to remain close to the UK average genetic merit for fat plus protein production. Approximately equal numbers of S and C cows are housed together and fed either a high or a low concentrate diet. Details of the management regime and selection criteria are reported elsewhere (Pryce *et al.*, 1999, Veerkamp *et al.*, 1995, Langhill 99 Annual Report). A separate data set was constructed for each of the four traits analysed. Milk yield data consisted of summed daily yield measured at morning and afternoon milking up to 305 days after calving. Records were removed if the value at any milking was less than 3 kg or more than 3 standard deviations from the mean of all other

records at the same stage of lactation. This resulted in the removal of 383 records from 194 different animals out of 459,027 individual milk recordings for all animals. BCS was assessed weekly on all cows by the same operator using a 0 to 5 scale with 0.25 intervals (Lowman *et al.*, 1976) where 0 is extremely thin and 5 is obese. LWT was measured weekly after morning milking coincidentally with condition scoring. Cows were fed *ad libitum* through Calan Broadbent gates. Daily FI was calculated from each of four consecutive days (Monday to Thursday) of FI measurements. Feed offered was weighed on one morning and refusals weighed and removed the following morning. Feed offered was adjusted over time so that refusals were nearly always greater than zero. Cows observed to habitually waste food by throwing were removed from the trial. Table 3.1 shows the number of observations for each trait.

A pedigree file was constructed from the complete Langhill database and consisted of 3080 records. There were 40 sires and 206 dams with progeny records in the dataset and 82 grand sires and 189 grand dams in the pedigree file.

3.3.2 Model

Variance component estimation was performed using a random regression animal model using the DxMRR statistical package (Meyer, 1998). The random regression model fitted in this study was;

$$y_{it} = F_{it} + \sum_{m=0}^{f-1} \beta_m P_m(t) + \sum_{m=0}^{k-1} \alpha_{im} P_m(t) + \sum_{m=0}^{k-1} \lambda_{im} P_m(t) + \varepsilon_{it}$$

where y_{it} represents the trait being evaluated for animal i at time t. F_{it} represents fixed effects of genetic line (2 groups), feed group (2 groups) and measurement group (year and week of measurement) and the covariates percentage North American Holstein genes (linear) and age at calving in months (linear and quadratic). β_m are the fixed regression coefficients, α_{im} and λ_{im} are the additive genetic and permanent environmental random regression coefficients and ε_{it} is the error associated with time *t*. $P_m(t)$ is the m^{th} Legendre polynomial evaluated at time *t* and the parameters *f* and *k* are the order of the fixed and random polynomial respectively. The four traits analysed separately were milk yield, condition score, feed intake and liveweight.

Based on the work of Olori *et al.,* (1999) and Brotherstone *et al.,* (2000), and preliminary analyses of these data, fixed regressions fitted for all traits were order 5 and, apart from BCS, random regressions fitted were order 3. For BCS, a likelihood ratio test indicated that using polynomials of order 4, to model both the additive genetic and permanent environmental random regression coefficients, yielded a significant improvement in fit. Quadratic or cubic polynomials were used to model the shape of the random curve for both the additive genetic and permanent environmental variances in this study, in contrast to Jamrozik and Schaeffer (1997) who fitted the permanent environmental effect as a single random effect.

Random regression models allow for repeated measurements taken at different stages of lactation and for different measurement errors associated with observations made over time. Errors and error variance associated with measurements made at different parts of a lactation vary; measurement errors may be larger at the beginning of lactation or when cows are drying off. Following initial analyses of BCS, LWT and FI, random errors were assigned to days 1 to 14, 15 to 99 and 100 to 250 representing the immediate *post partum* period, the ascending and peak period and the descending phase respectively. Initial analysis of milk yield indicated that measurement errors were not homogeneous during the early part of lactation, so the first 15 days of lactation was split into 5 measurement error classes each of 3 days. Breeding values were calculated for all animals in the data, for all traits for days of lactation 1 to 250.

3.3.3 Energy Calculation

In order to convert breeding values for bulls into energy equivalents, the Effective Energy system described, in part for cows, by Emmans (1994) was used. This model accounts for the costs of processing of energy from the ingested feed. Details of the formulae used to convert traits to effective energy equivalents are in Appendix A. When energy balance is defined as the difference between ingested and expended energy over a sufficiently short time-scale (e.g. 1 day), then it can be estimated from daily feed and production variables that include 'fixed' costs such as maintenance and activity. When considered over a longer time frame (e.g. 1 week) it can also be estimated from body state changes that, in turn, can be estimated from LWT and BCS. With no error of measurement, a perfect system of calculation, and mature animals, these terms would sum to zero. In order to calculate energy

balance from body state changes, formulae are required that convert BCS and LWT into weights of lipid and protein. From these values maintenance and activity requirements can be calculated. Energy balance was calculated both ways for each bull after converting all measures to energy equivalents using the effective energy system of Emmans (1994) with additional terms for the major organic components of milk.

EB1 = energy consumed (EEI) – energy for (milk (EE(y)) + maintenance (EE(m)) + activity (EE(a))) (equation 3.1)

EB2 = energy in (lipid mobilised or stored (EEL) + protein mobilised or stored (EEP)) (equation 3.2)

The method of calculating energy values from observed measures is given in Appendix A.

Both methods of calculation were used in order to compare them and to assess the suitability of calculating energy balance from LWT and BCS. LWT can be predicted with reasonable accuracy from type traits (Koenen and Groen, 1998) and BCS is routinely classified in the national population, making the calculation of energy balance feasible for those cows participating in the national type evaluation scheme.

Each diet offered was sampled daily and combined to form a weekly sample. These weekly samples were then analysed at the end of each year's trial. The mean values of the feed components used in the calculation of energy balance were: dry matter (DM) 315 g/kg fresh matter, metabolisable energy 11.8 MJ/kg DM, crude protein 176.5 g/kg DM, organic matter 918.7 g/kg and in vitro determined digestibility of organic matter 772.9 g/kg. The means for other traits were: 4.32% fat, 3.23% protein and 4.76% lactose in the milk and 45.1 kg fresh feed/day, 555 kg liveweight and condition score 2.44. Milk samples were analysed weekly for both morning and afternoon milking.

3.4 RESULTS

Overall means and SD for each trait are given in Table 3.1. Least square mean phenotypic values, which include the appropriate fixed effect solutions, for each trait by day of lactation are presented in

Figures 3.1 and 3.2 for MY, FI and LWT and BCS respectively. Heritabilities for the four traits from day 1 to 250 are given in Figure 3.3. The sudden change in the heritability estimates at day 14 for FI and LWT indicates that the error variance is substantially different within the first 14 days compared to the remainder of the lactation. This is because measurement errors were (incorrectly) considered homogeneous during the first 14 days of lactation. In future studies, consideration should be given to further subdividing the classes of measurement error within this period. An alternative would be to fit a continuous function to model the measurement error over the course of the lactation, hence avoiding the assumption of homogeneity of variance in the intervals. Note also that there are fewer animals in the milking herd in the first few days after calving leading to smaller numbers of observations in early measurement error classes (Table 3.4).

Error variances for LWT, FI and BCS are given in Table 3.2 and those for milk yield are in Table 3.3. The error variance for milk yield in the first three classes is substantially higher than in the later part of early lactation and does not approach values reported from other studies until day 10 (Olori *et al.*, 1999; Brotherstone *et al.*, 2000). Since energy balance in very early lactation is of interest in this study, all observations were included. In many other studies, data collected before day 4 are discarded as unreliable. The mean and standard deviation for milk kg by day of lactation for the first 14 days are given in Table 3.4. The error variance from the analysis for days 1 to 14 is substantially higher than expected from the standard deviations of the raw data (Table 3.4). Furthermore, the error variance from the analysis changes substantially whilst the SD from the raw data is reasonably constant. This indicates that the polynomial model had difficulty fitting the data during that period when there were fewer observations.

Genetic correlations between daily FI, LWT, milk yield and BCS are given in Tables 3.5, 3.6, 3.7 and 3.8 respectively, for a representative selection of days in milk. For milk yield and BCS, correlations declined from near unity between adjacent observations to 0.16 (milk yield) and 0.17 (condition score) between days 7 and 247. Genetic correlations between LWT at all stages of lactation were high. Veerkamp and Thompson (1999) also obtained high genetic correlations between daily LWT measurements. They estimated a genetic correlation of 0.79 between LWT in week 1 and LWT in

week 15, which is consistent with our estimate of 0.86 between days 7 and 97. Genetic correlations between daily FI followed a slightly different pattern from that of the other traits considered. Correlations between early and mid-lactation were low, or slightly negative, but high between early and late lactation. Genetic correlations between mid and late lactation for FI were also low.

Breeding values for a bull are expressed as deviations from the average curve for all animals. Breeding values for all traits for two well-known bulls with very different breeding values for type and production are given in Figures 3.4 and 3.5. These bulls were chosen to demonstrate the differences between extreme bulls, and were taken from the 40 represented in the data. Figure 3.4 is for a popular bull of traditional British Friesian type used to sire control line cows and with below average linear type scores for angularity and stature indicating that average daughters are of lower body weight and higher BCS than the average for all bulls. The bull has very low breeding values for milk production and LWT at the start of lactation which increase towards the end of lactation. Breeding values for mean feed intake follow a curvilinear trajectory with a peak in mid lactation. Condition score increases marginally as lactation progresses. These values combined suggest that the bull produces low yielding daughters that do not mobilise body tissue and continue to grow as heifers as the lactation proceeds rather than partitioning energy towards milk production. In contrast, Figure 3.5 shows above average breeding values for the 4 traits for a typical Holstein bull used to sire selection line cows. The average daughter of this bull, as a heifer, would lose body weight and condition and increase milk yield relative to the mean as lactation progresses. A yield curve that increases as the lactation progresses indicates a daughter average yield that is higher at the end of lactation than daughters of other bulls i.e. the lactation is more persistent. Feed intake follows a similar curvilinear trajectory but does not decline as much at the end.

Condition score profiles found in this study are similar in shape to the genetic curves reported by Jones et al. (1999), supporting their comment that some daughters appear to lose body condition and not regain it towards the end of lactation. For these daughters to be in a similar body condition at the start of the next lactation, then body tissue deposition must take place outside the window of observation in these 2 studies. This must be at the end of lactation and in the dry period.

The mean genetic energy balance curve (including the appropriate fixed effect solutions) for all bulls with at least 10 daughters in the dataset calculated from feed intake and milk production output (EB1, equation 3.1) is given in Figure 3.6. Its shape is consistent with that from other reported work on phenotypic analysis of production data. A large negative balance at the start of lactation becomes positive after about day 40 and remains so until the end of lactation. This is consistent with other reported energy balance curves for heifers (De Vries *et al.,* 1999; De Vries and Veerkamp, 2000). Energy balance for the same bulls, calculated from body state changes (EB2, equation 3.2), is given in Figure 3.7. This curve also depicts a large negative balance at the start of lactation, but shows that a return to positive energy balance is not attained until day 87. This suggests that long-term body state changes may lag behind daily intake and output measures. The cumulative energy state calculated using EB2, in terms of MJ energy lost or retained relative to energy content at calving, of the average bulls' daughter is given in Figure 3.8. The body energy lost in early lactation is not regained fully until day 200 after which the animal begins to further accumulate body energy. In this study, animals were in their first lactation and so would still be expected to be growing at the end of lactation and accumulating protein as well as lipid.

3.5 DISCUSSION

Traditional evaluations for productivity in dairy cattle assume that the trait being evaluated is uniformly expressed during the period of measurement and evaluation. Hence, a 305 day lactation forms the basis of production evaluations in most countries. Two animals of equal estimated genetic merit are assumed to have produced the same amount of milk over 305 days and no allowance is made for the relative proportions of milk produced within given parts of the lactation. More recently, research has focused on test day models as a mechanism for evaluating dairy cattle during the course of the lactation, resulting in genetic evaluations which account for differences in the lactation curve between cows (Schaeffer and Dekkers, 1994; Jamrozik and Schaeffer, 1997). Genetic evaluations are expressed on a daily basis allowing predicted transmitting abilities for persistency to be derived. This raises the possibility of selection indexes that include the parameters of the lactation curve and

therefore selection of animals that express genetic merit for production during different parts of their lactation or even lifetime.

Lactations that have a lower peak and the same total yield have been proposed as more desirable because of the apparent benefits to cow welfare resulting from the lactation being more persistent (Dekkers et al., 1998). Other benefits may arise such as improved health and fertility as a result of a lower rate of body energy loss due to a lower peak yield. However, others have suggested that persistency of lactation *per se* may not be desirable because of the unclear relationship between reproductive capacity and lactation shape (Swalve and Gengler, 1999). A change in the profile of milk production may have consequences for the profile of body tissue loss and gain and the growth curve of a first lactation cow, in the absence of any change in the pattern of feed intake.

Heritabilities for milk yield found in this study are consistent in magnitude with those reported by Veerkamp and Thompson (1999), but lower than those from Olori *et al.* (1999) and Jamrozik and Schaeffer, (1997). All reported heritabilities are generally higher than those estimated from national data using conventional evaluation techniques. This is likely to be a result of the higher standard of recording used in experimental farms for traits with large random error components, such as BCS and LWT. The change in heritability as lactation progresses has a biological explanation through changes in nutrient partitioning. It is anticipated that nutrient partitioning has a genetic component and different genes will exert their action as endocrine and physiological changes in the cow take place as lactation proceeds. For example, from an evolutionary viewpoint, the current calf will require less milk over time to survive and the cow will alter the emphasis from ensuring the current calf survival to that of the impending next pregnancy. This may shift nutrient partitioning away from lactation to reproduction and maternal tissue replacement and eventually to the conceptus in the event of a successful mating.

The role of leptin in the energy balance/reproductive axis has recently been reported (Holness *et al.*, 1999) and is implicated as a messaging mechanism between reproduction and pregnancy and the maternal energy status. It is likely that genetic selection for production has altered the relative

partitioning of nutrients between competing systems in high yielding dairy cows. Identification of genes implicated in energy balance during lactation may enable future selection to concentrate on the optimum energy balance profile that satisfies the prevailing economic circumstances. In a market environment where calves have little value, and the risk and welfare considerations associated with parturition are high, partitioning energy towards reproduction may not be economically justified.

Low, or even negative, genetic correlations between milk yields in early and late lactation have been obtained by other researchers (Jamrozik and Schaeffer., 1997; Brotherstone et al., 2000), possibly reflecting problems in modelling the association between yield early in lactation and later lactation yields. For condition score, genetic correlations were low to moderate between scores in early and late lactation but otherwise correlations were close to unity. Jones et al. (1999) obtained similar results in an analysis using national type classification data and concluded that BCS in early lactation is under different biological control to BCS at other stages of lactation. Genetic correlations between daily LWT measures were high and it may be possible to analyse these data with a simple repeatability model, which assumes a genetic correlation of unity between observations. Although LWT is not routinely recorded, Veerkamp and Brotherstone, (1997) demonstrated a close association between LWT and some type classification traits routinely recorded in the national population. Koenen and Groen, (1998) also showed that genetic evaluations for LWT could be calculated using linear type measures.

Genetic correlations between daily FI records followed a different pattern, in that there were moderate to strong correlations between early and late lactation observations, but no association was detected between early and mid-lactation and also mid-lactation and late lactation. This may be due to different genetic control of nutrient partitioning at the beginning and end of lactation associated with the current calf and the impending pregnancy respectively. At both the beginning and end of lactation there is a strong influence of reproduction on lactation. In the first few weeks of lactation, in a natural environment, the cow has to feed and protect the current calf, recover from parturition and feed herself. It is likely that her own self interests are of the lowest priority and so lactation is fuelled to a large extent by body tissue mobilisation (Pond and Newsholme, 1999). At the end of lactation, the

growing foetus is placing more demands on the cow. The cow's long term energy status objectives may exert more of an influence at this stage on energy balance by having a depressive effect on lactation in order to favour body tissue replenishment. The decline in positive energy balance towards the end of lactation would signal the attainment of a long-term neutral energy status determined in part by genotype, and the effects of pregnancy.

The mean energy balance curves calculated from feed and production measures (Figure 3.6) and from body state changes (Figure 3.7), for bulls represented in this dataset were consistent with those reported elsewhere from a phenotypic analysis (De Vries and Veerkamp, 2000). Calculating energy balance from breeding values of the individual traits gives a genetic energy balance curve. The purpose of calculating energy balance from production parameters, and from body state changes for the same animals, was to assess the usefulness of body measurements in calculating energy balance for national populations for which FI measurements are not available. Gross body energy state changes are easy to estimate over long periods e.g. BCS at the beginning and end of lactation. It is likely that energy balance calculated from body tissue mobilisation will be more accurate over a longer period of time, but more variable over a short time period, than energy balance calculated from FI measures. The reduction in energy intake seen at the end of lactation in Figure 3.6 is unlikely to be real, given the accumulation of body reserves towards the end of lactation as shown by Figure 3.8. It is likely to be due to the effect that pregnancy has on the prediction of body components from LWT and BCS for which no allowance could be made. The method of estimation of body lipid, which relies on visual and tactile appraisal, may be more accurate when the animal is losing, rather than gaining, body lipid or when the animal is thin rather than fat. In addition, the values of the parameters in the formulae to predict body components from LWT and BCS measures were derived from mature, non-pregnant Friesians (Wright 1982) and will not be entirely appropriate for modern Holstein heifers that become pregnant during lactation. The use of first lactation cows in this study adds a component of lipid-free growth to the energy balance calculation. Figure 3.8 shows that these animals only pass their starting body energy state after day 200 of lactation. It would be interesting to study the effect of the duration of this body energy loss on health and fertility in the subsequent parity, and to determine any genotype by environment interactions for lifetime energy balance profiles.

Energy balance may be a more suitable candidate for selection, even though it is a composite of at least two other traits that require recording. In the first case it is a composite of milk yield and composition, and feed intake and, in the second case, a composite of liveweight and condition score change. The magnitude and duration of energy balance fluctuations could be a risk factor contributing to disease, infertility and a shorter lifespan. The legacy of a negative energy balance of substantial magnitude and duration may manifest itself in subsequent lactations. If so, selection for a flatter energy balance profile may be more beneficial than selection for persistency *per se.* National energy balance breeding values for bulls may be possible using linear type traits to predict body weight and condition score measures.

3.6 CONCLUSIONS

Energy balance is the outcome of the combined influence of a number of traits that are shown to be under genetic control which varies throughout lactation. Random regression techniques can be used effectively to calculate breeding values for these traits over time and therefore to produce breeding value profiles for energy balance for dairy bulls. Energy balance profiles can be calculated from traits describing body tissue mobilisation as well as from feed intake and milk output. It may be possible to use nationally recorded data to predict liveweight and therefore calculate breeding values for energy balance for bulls at the national level.

Appendix A.

3.7.1. Equation to predict gut fill (GF, kg) and empty body weight (EBW, kg)

GF = DMI*(11-(7*MEC/15))

EBW = BW – GF

MEC=ME/kg DM; DMI = dry matter intake, kg/d

BW is body weight (kg) as weighed.

3.7.2. Equation to predict lipid (L, kg) and protein (P, kg) weights in the empty body

L = EBW*0.120*(BCS - 0.36)

P = 0.2224*EBW*(1-(0.120*(BCS - 0.36)))

BCS is condition score measured on a 0 to 5 scale. The values of the parameters were derived from the data of Wright (1982) for mature Friesian cows.

3.7.3. Equations to predict the metabolisable energy content, MEC MJ/kg OM from OM (organic matter) content and InvitroOMD (organic matter digestibility) and to predict the effective energy content (EEC) of the feed.

CP (kg/kg OM) = CP(kg/kg DM)/OM

MEC (MJ/kg OM) = InvitroOMD*16/OM

DCP (kg/kg OM) = 0.9*(CP (kg/kg OM) – 0.035)

EEC(MJ/kg OM) = 1.15*MEC – 3.84 –4.67*DCP

OMI(kg/day) = DMI*OM*0.001

EEI(MJ/day) = OMI * EEC

CP is crude protein

DMI and OMI are dry and organic matter intakes (kg/d) respectively

EEC is effective energy content of the diet (MJ/kg OM)

EEI is effective energy intake (MJ/d)

OM is organic matter content (kg/kg DM)

3.7.4. Equation to predict EE needed for milk, EE(y) (MJ/d)

EE(y) (MJ/day) = MY*((0.33*%protein) + (0.18*%lactose) + (0.56*%fat))

MY is milk yield (kg/d)

3.7.5. Equations to predict EE needed for, or yielded by, body component changes

EE yielded by protein loss 13.5 MJ/kg

EE yielded by lipid loss 39.6 MJ/kg

EE needed for protein gain 50 MJ/kg

EE needed for lipid gain 56 MJ/kg

3.7.6. Equation to predict EE needed for maintenance, EE(m)

$EE(m) = M_e * P / (P_m)^{0.27}$ MJ/day

For a modern Holstein cow P_m is estimated at 120 kg and the value of M_e is 1.63, so that

EE(m) = 0.4475*P MJ/day.

The activity allowance for Langhill, EE(a),is taken to be

EE(a) = 0.01* BW MJ/day

Figure 3.1. Least square mean phenotypic values by day of lactation for Feed Intake, Liveweight and Milk Yield. (▲=Liveweight, □=Milk Yield, ■=Feed Intake)

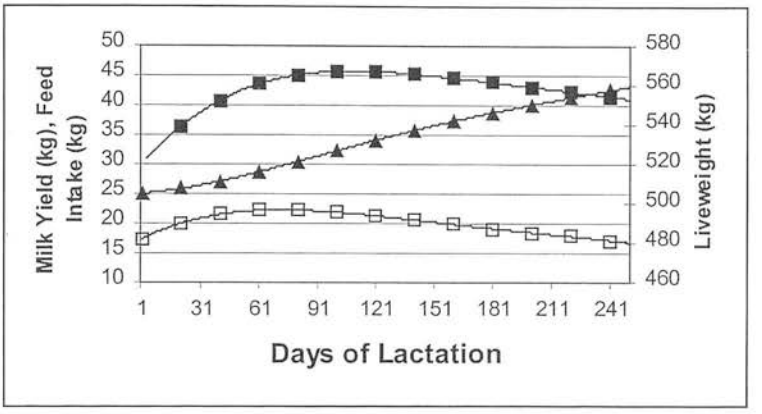


Figure 3.2. Least square mean phenotypic values by day of lactation for Condition Score

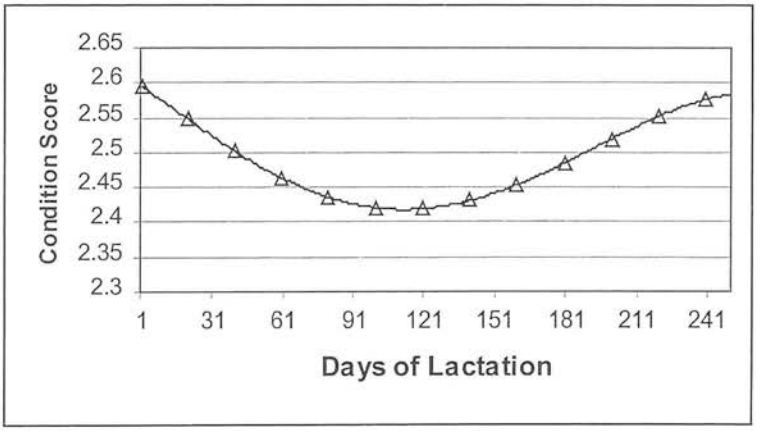


Figure 3.3. Heritabilities by day of lactation for Condition Score, Feed Intake, Liveweight and Milk Yield. (▲=Liveweight, □=Milk Yield, ■=Feed Intake, Δ=Condition Score)

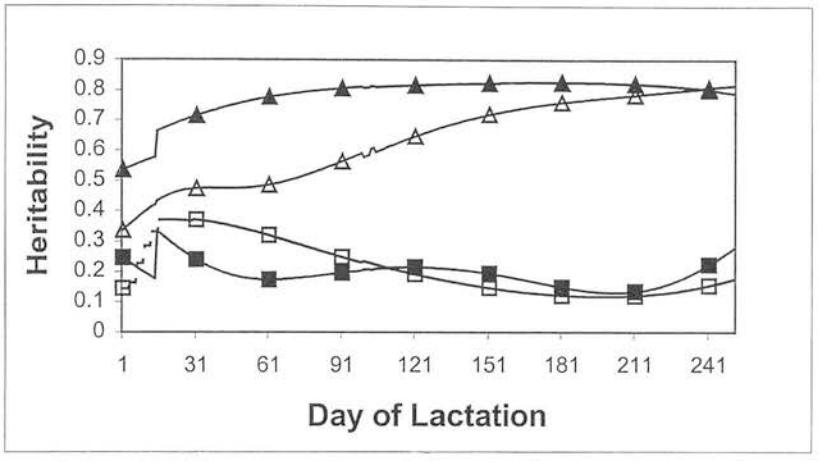


Figure 3.4. Breeding values by day of lactation for Bull A, a popular bull of typical Friesian type, for milk yield, feed intake (FI), condition score (CS) and liveweight. (▲=Liveweight, □=Milk Yield, ■=Feed Intake, Δ=Condition Score)

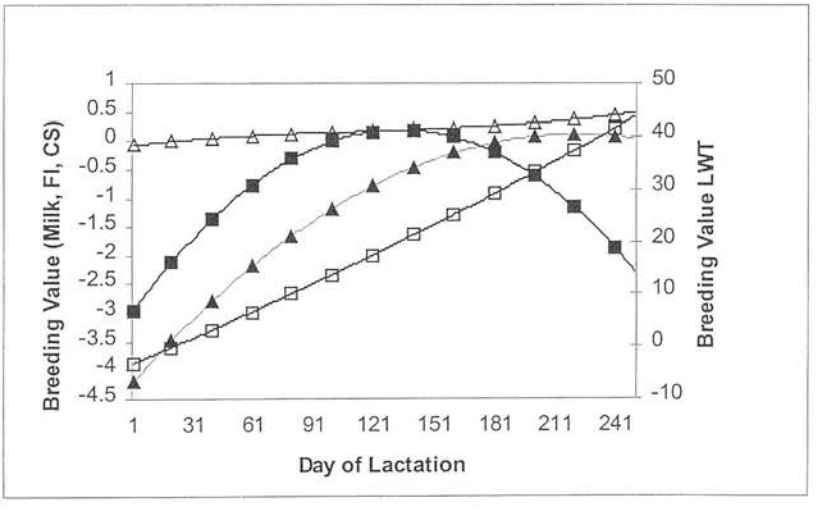


Figure 3.5. Breeding values by day of lactation for Bull B, a popular bull of typical Holstein type, for milk yield, feed intake (FI), condition score (CS) and liveweight. (▲=Liveweight, □=Milk Yield, ■=Feed Intake, Δ=Condition Score)

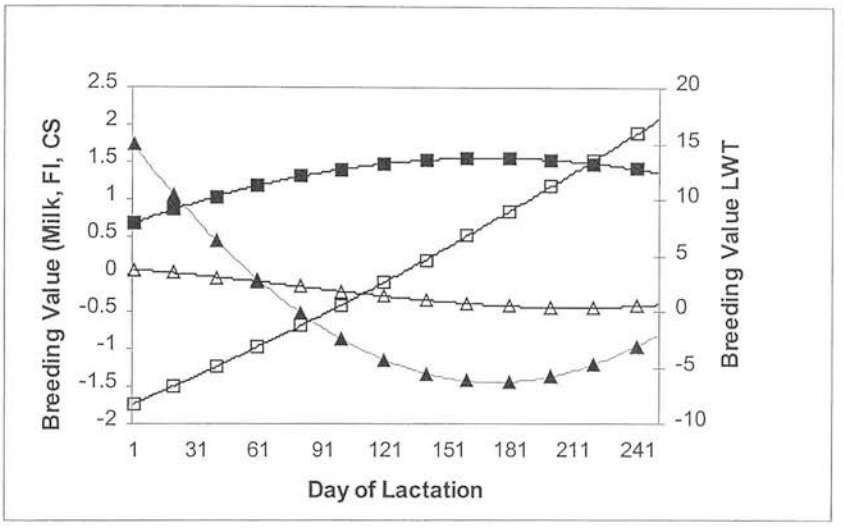


Table 3.1. Number of animals and observations per animal for each trait and mean and SD for all observations for each trait.

Trait	Animals	Max obs per animal	Mean	SD
Milk Yield kg/d	298	303	21.2	5.9
Feed intake kg fresh/d	297	141	45.0	8.7
Condition score	297	42	2.45	0.48
Liveweight kg	297	44	551	58

Table 3.2. Error variance for feed intake (FI), liveweight (LWT) and condition score (CS) for each measurement error class.

	FI (kg^2)	LWT (kg^2)	CS
1-14 days	62.5	399.2	0.012
15-99 days	18.4	126.5	0.012
100-305 days	17.9	139.4	0.014

Table 3.3. Error variance for milk yield for each day of lactation class.

	Milk (kg^2)
1-3 days	50.8
4-6 days	41.1
7-9 days	22.1
10-12 days	12.5
13-15 days	7.4
16-29 days	4.1
30-99 days	3.8
100-305 days	3.1

Table 3.4. Number of records, mean and SD of milk yield for the first 14 days of lactation.

Days	Count	Mean Milk Yield (kg)	SD milk yield (kg)
1	1	10.1	NA
2	4	10.7	4.36
3	22	15.7	3.63
4	106	16.4	3.99
5	206	16.7	4.26
6	230	17.6	4.52
7	233	18.4	4.25
8	232	19.2	4.27
9	240	19.8	4.21
10	245	20.2	4.14
11	237	20.8	4.36
12	238	21.5	4.33
13	247	21.7	4.47
14	243	22.12	4.38

Table 3.5. Genetic correlations between feed intake on different days of lactation (above diagonal). Heritabilities are on the diagonal in bold.

Day	7	37	67	97	127	157	187	217	247
7	**0.22**	0.89	0.44	0.06	-0.07	-0.04	0.21	0.65	0.87
37		**0.22**	0.80	0.51	0.39	0.41	0.59	0.82	0.78
67			**0.17**	0.92	0.86	0.86	0.90	0.77	0.41
97				**0.20**	0.99	0.98	0.93	0.60	0.11
127					**0.21**	0.99	0.92	0.55	0.03
157						**0.19**	0.95	0.62	0.11
187							**0.14**	0.83	0.40
217								**0.14**	0.85
247									**0.24**

Table 3.6. Genetic correlations between liveweight on different days of lactation (above diagonal). Heritabilities are on the diagonal in bold.

Day	7	37	67	97	127	157	187	217	247
7	**0.56**	0.97	0.91	0.86	0.82	0.79	0.77	0.77	0.77
37		**0.73**	0.98	0.96	0.94	0.92	0.91	0.90	0.90
67			**0.79**	0.99	0.98	0.97	0.96	0.96	0.96
97				**0.81**	1.00	0.99	0.99	0.98	0.98
127					**0.82**	1.00	1.00	1.00	0.99
157						**0.83**	1.00	1.00	1.00
187							**0.83**	1.00	1.00
217								**0.82**	1.00
247									**0.80**

Table 3.7. Genetic correlations between milk yield on different days of lactation (above diagonal). Heritabilities are on the diagonal in bold.

Day	7	37	67	97	127	157	187	217	247
7	**0.23**	1.00	1.00	0.98	0.95	0.89	0.75	0.49	0.16
37		**0.36**	1.00	0.99	0.97	0.91	0.78	0.53	0.20
67			**0.30**	1.00	0.98	0.93	0.81	0.58	0.25
97				**0.23**	0.99	0.96	0.86	0.64	0.33
127					**0.18**	0.98	0.91	0.73	0.44
157						**0.14**	0.97	0.84	0.59
187							**0.12**	0.94	0.77
217								**0.12**	0.94
247									**0.17**

Table 3.8. Genetic correlations for condition score (CS) on days of lactation above diagonal. Heritabilities are on the diagonal in bold.

Day	7	37	67	97	127	157	187	217	247
7	**0.38**	0.87	0.59	0.38	0.25	0.18	0.15	0.14	0.17
37		**0.48**	0.91	0.77	0.68	0.62	0.60	0.60	0.63
67			**0.50**	0.97	0.92	0.89	0.88	0.88	0.89
97				**0.58**	0.99	0.98	0.97	0.97	0.96
127					**0.67**	1.00	1.00	0.99	0.98
157						**0.73**	1.00	1.00	0.98
187							**0.77**	1.00	0.98
217								**0.79**	0.99
247									**0.81**

Figure 3.6. Energy balance calculated from energy intake and expenditure (EB1).

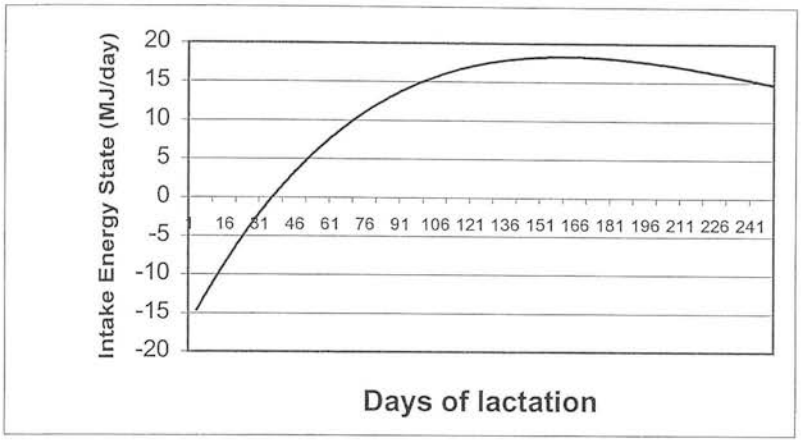


Figure 3.7. Energy balance calculated from body energy changes (EB2).

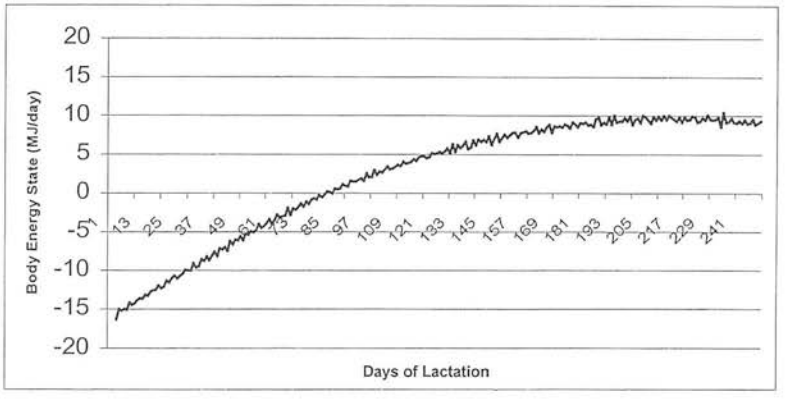
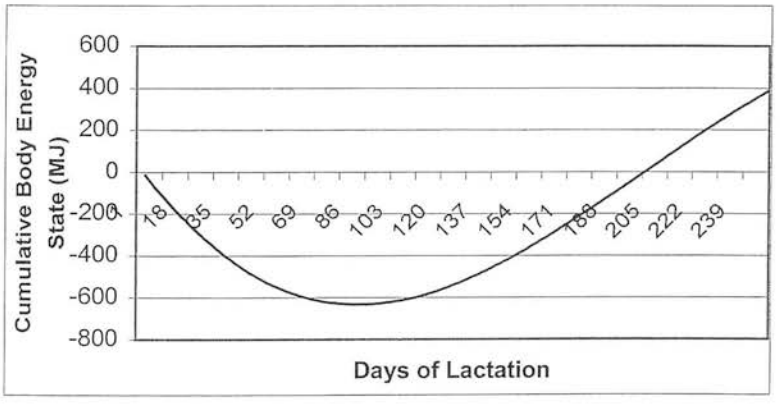


Figure 3.8. Cumulative long-term body lipid energy state relative to body lipid energy content at calving.



CHAPTER 4

Energy Balance Profiles For The First Three Lactations of Dairy Cows Estimated Using Random Regression

4.1 SUMMARY

Daily animal solutions were predicted using random regression analysis for feed intake, milk yield, liveweight and condition score recorded on 189 cows at the Langhill Dairy Cattle Research Centre. All cows had three successive lactations. Energy balance for days 1 to 305 of each of the three lactations was calculated both from daily measures of feed intake and milk output and from weekly measures of liveweight and condition score. Cows returned to positive energy balance at days 72, 75 and 95 in lactations 1, 2 and 3 respectively based on energy balance calculated from feed intake and milk output records (EB1), and at days 77, 83 and 73 based on energy balance calculated from body energy state changes (EB2). Correlations between energy balance at the same time in successive lactations ranged from 0.01 to 0.66 depending on the method of calculation and the stage of lactation.

Energy balance over 3 lactations was modelled using sinusoidal functions which were associated with individual cows and allowed to vary between cows. The parameters of these curves are potentially useful since they have a biological interpretation. The phase relates to the period from calving to return to positive energy balance and the amplitude relates to the degree of body energy loss (and recovery). The sinusoidal functions fitted to the curve removed a significant proportion of the variation but accounted for only 45% and 40% of the variation in EB1 and EB2 respectively.

The relationship between energy balance in the first 3 lactations is likely to be more complex than a simple linear function but the profile of energy balance over the first 3 lactations may be a useful selection criteria in a multi-trait index. Energy balance profile over lactations 1 to 3 can be modelled with moderate accuracy using sinusoidal functions and this warrants further research.

Abbreviations: Milk Yield (**MY**); Liveweight (**LWT**); Body Condition Score (**BCS**); Feed Intake (**FI**)

4.2 INTRODUCTION

The total energy required by a cow to produce a lactation's yield of milk can vary depending on the source of energy to the mammary gland, since there is variation in the cost of metabolic processing of different types of nutrients by the cow (Emmans, 1994). If the cow can consume sufficient energy in food on a daily basis, then the cost in energy terms is simply the cost of turning the daily feed into milk minus the cost of supporting the obligatory bodily functions of the cow. However, if the cow cannot or will not consume sufficient feed on a daily basis the energetic cost of producing milk must then include the energetic cost of catabolising body tissue to make it available for milk production. There is genetic variation in the profile of body condition score (BCS) of a bull's daughters (Jones et al. 1999), indicating that a cow may have a genetically determined body energy state that is in part a function of stage of lactation. In order to remain in a preferred body energy state at all stages of lactation, as suggested by genetic merit for body condition score the cow must subsequently replace lost body energy. This replacement also has an energetic cost of processing. Therefore, in addition to the cost of obligatory functions, the total energetic cost of producing a whole lactation's worth of milk is the sum of the energetic content of the milk and the cost of mobilising and replacing body tissue.

The replacement of body tissue in modern dairy cows usually takes place later in the same lactation, once milk output begins to decline. If the cow is pregnant, then yield is further depressed (Olori et al., 1997) as the foetus develops. Replenishment of body tissue in preparation for the next lactation creates competition for nutrients amongst the demands for current yield and the developing foetus. The use of body lipid as a nutritional buffer is a normal mammalian physiological process (Pond et al., 1999) but the biological rules determining priorities of use, or partitioning, of available nutrients in cows of different genetic merit for production and at different stages of lactation and gestation are unknown.

The term energy balance is often used to describe the body energy state of dairy cows which is the outcome of daily energy flux; negative energy balance is associated with body energy loss and positive energy balance with body energy gain. Cows which lose body tissue, and hence energy, in early lactation usually return to positive energy balance at around 40 to 80 days *post partum* (Sutter et

al., 2000; Chapter 3; Veerkamp et al., 2000). Kendrick et al. (1999) found that return to positive energy balance was at 21 days or 49 days with high or low energy diets respectively. However, cumulative body energy loss in the first lactation is, on average, only fully recovered at around day 200 as shown in Chapter 3. Continued growth is required through the dry period and into the second lactation in order to reach physiological maturity. Negative energy balance is related to some health traits (Collard et al., 2000), to resumption of reproductive activity (De Vries et al., 1999, Veerkamp et al., 2000) and to oocyte size and quality (Beam and Butler 1999, Kendrick et al., 1999). Individual cows may not regain all lost body energy in the first lactation leading to a greater deficit to be replenished in the second. This may result in carry-over effects from one lactation to the next, on both yield and non-yield traits such as health and fertility.

It is important to view productivity over the cows entire lifetime and not simply on a single lactation basis. Current and previous body energy state changes may create a legacy that affects current and future productivity and health and fertility. Parameters of the lactation curve are different between at least the first three lactations although curve parameters from one lactation can be used to predict those of subsequent lactations. Friggens et al. (2000) found that parameters associated with peak lactation and the rate of decline after peak in the third lactation can be described as simple ratios of those parameters in the first and second lactations. This is important when considering energy balance across lactations for the same animals when measures are available only in the first lactation, or where subsequent lactation measures may be biased by selection. The use of random regressions and Fourier series allows modelling of cyclical changes in a trait over seasons (Meyer, 2000) and could be used to model lifetime (or at least multiple lactation) energy balance changes in dairy cows. Parameters of these cyclical functions might then be analysed for relationships with traits of economic importance such as health, fertility and survival. The objectives of this study were 1) to model phenotypic daily milk yield, fresh feed intake, liveweight and condition score using random regression techniques and restricted maximum likelihood (REML) for traits measured at different times and with different frequencies on dairy cows from the Langhill Dairy Cattle Research Centre; 2) to combine those daily estimates obtained in objective 1) into an overall energy balance for each day of the first three

successive lactations; 3) to compare energy balance curves over three lactations; and 4) to investigate the feasibility of modelling energy balance in the first three lactations using harmonic analysis.

4.3 MATERIALS AND METHODS

Data on 189 animals were extracted from the database of Langhill records collected since 1990 and that had completed at least 26 weeks of the third lactation by July 1999. The data included records of milk production and composition, liveweight (LWT), body condition score (BCS) and fresh feed intake (FI) for two lines of cows. The lines have been selected either for kg fat plus protein (select line (S)) or selected to remain close to the UK average genetic merit for fat plus protein production (control line (C)). Approximately equal numbers of S and C cows were housed together and offered either a high or a low concentrate diet for a minimum of 26 weeks and for a maximum of 38 weeks of each lactation. Details of the management regime and selection criteria are reported elsewhere (Pryce et al., 1999). Records for animals that had remained on the trial for their first 3 lactations were the only ones included, to enable the analysis of multi-lactation energy balance for the same set of animals. A separate dataset was constructed for each of the four traits analysed (milk yield, condition score, liveweight and feed intake). Milk yield (MY) data consisted of summed daily yield measured at morning and afternoon milking up to 305 days after calving. In order to eliminate recording errors and aberrant records due to illness or oestrus, milk records were removed from the main dataset if the value at any milking was less than 3 kg or was more than 3 standard deviations different from the mean of all other records for the same parity at the same stage of lactation. This resulted in the removal of 710 records out of 568,380 individual daily recordings from 224 different animals from the main dataset. Of these, only 11 animals had more than 10 daily records removed. Condition score was assessed weekly on all cows by the same operator over the entire period of record collection using a 0 to 5 scale with 0.25 intervals (Lowman et al., 1976) where 0 is thin and 5 is obese. Liveweight was measured weekly after morning milking coincidentally with condition scoring. Food was available *ad libitum* and individual intakes were recorded through Calan Broadbent gates. Daily FI was calculated from each of four consecutive days (Monday to Thursday) of measurements of food offered and refused. Feed offered was weighed on one morning and refusals weighed and removed the following morning. Feed offered was adjusted over time so that refusals were around 10% of the total offered.

Cows observed to habitually waste food by throwing it were removed from the trial. Table 4.1 shows the number of observations for each trait for each lactation.

Variance component estimation was performed using a random regression model with the ASREML statistical package (Gilmour, 1998). As pedigree information was not included in the analysis, animal solutions are combined animal genetic and permanent environmental effects. The random regression model fitted in this study was:

$$y_{it} = F_{it} + \sum_{m=0}^{f-1} \beta_m P_m(t) + \sum_{m=0}^{k-1} \lambda_{im} P_m(t) + \varepsilon_{it}$$

where F_{it} represents fixed effects of genetic line (2 groups), feed group (2 groups) and time of measurement (year and week of measurement) and the covariates percentage North American Holstein genes (linear) and age at calving in months (linear and quadratic) for animal *i*. β_m are the fixed regression coefficients, λ_{im} are the random regression coefficients associated with the animal plus its permanent environment and ε_{it} is the residual error associated with days since calving *t*. $P_m(t)$ is the m^{th} Legendre polynomial evaluated at *t* and the parameters *f* and *k* are the order of the fixed and random polynomials respectively. Legendre polynomials were used because they are easy to manipulate, have good convergence properties and, being orthogonal polynomials, correlations between coefficients are lower than between the coefficients of ordinary polynomials. The four traits analysed separately by lactation were milk yield, condition score, feed intake and liveweight. Residual, or measurement, errors were expected to have heterogeneous variances over each lactation, with larger variances at the beginning of lactation and around peak yield. Different residual errors were therefore associated with observations over time. Based on preliminary analyses, residual error classes were defined as days 1 to 6, 7 to 9, 10 to 12, 13 to 15, 16 to 29, 30 to 99 and 100 to 305. Within classes, residual errors were assumed to be homogeneous. Ideally, I would have preferred to model the residual variances using a continuous function but an attempt to do so failed due to problems with convergence.

Based on previous genetic analyses of these data in Chapter 3, fixed regressions, which model the general shape of the curve and are common to all animals, were fitted for all traits as polynomials of

order 5. Third and fourth order polynomials were used to model the animal effect, and the goodness of fit was compared using a likelihood ratio test based on the χ^2 distribution and a significance level of 0.05 with the number of degrees of freedom equal to the difference in the number of variance components to be estimated.

Animal solutions obtained from the analysis were used to calculate daily phenotypic values for all animals in the dataset, for all traits for days of lactation 1 to 305. Energy balance was derived in two different ways for the same cows after converting all measures to energy equivalents using the effective energy system of Emmans (1994) with additional terms for the major organic components of milk. The first method of deriving energy balance (EB1) was based on predicted energy available from recorded feed consumption minus energy required for recorded daily milk production and maintenance predicted from LWT and gut fill. The second method (EB2) used body protein and lipid changes predicted from LWT and BCS. Details of the formulae used to convert traits to effective energy equivalents are given in Appendix A of Chapter 3. Using these formulae allows a comparison of methods of calculation and sources of data. Applying these formulae to data from successive lactations also allows an assessment of the usefulness of first lactation energy balance in predicting energy balance in the second and third lactation for each of the methods of calculation.

The component values used in the calculation of energy content of feed and milk were determined in 2 ways: 1) as the average over the whole dataset used for each trait, and 2) from results of feed and milk analyses concurrent with the time period in which the food was eaten or milk produced. This will enable a comparison of energy balance calculated using different data sources for the subsequent purpose of using national data where feed intake and feed energy analysis are not available. Feed samples were taken daily and pooled for weekly analysis of components. Milk samples were taken weekly at both milkings on one day and analysed separately by an official recording agency (Cattle Information Service, Scotland) using a Foss Milkoscan 605 (Foss, Denmark). Milk energy output for each day was calculated from daily yields and weekly milk sample analysis and feed energy intake was calculated from feed intake and the latest feed analysis.

The effects of pregnancy on the prediction of body weight were accounted for in part by modelling conceptus total weight (foetus plus placenta plus fluid) using an exponential growth curve from day of conception since Jakobsen et al. (1957) showed that energy requirements for the conceptus of heifers rose exponentially through gestation. For lactations 1 to 3, this curve resulted in a weight of conceptus at 280 days of gestation of 80, 90 and 100kg respectively to account for assumed increases in weight of this component in larger cows. The daily predicted weight of conceptus was subtracted from empty body weight to reduce any upwards bias on body lipid estimation by the presence of conceptus.

A visual appraisal of a sample of energy balance curves over 3 lactations for individual cows suggested that a possible method of describing the fluctuations in energy balance across lactations might be by using sinusoidal functions. All cows calved approximately every 12 months in order to remain on the trial, so energy balance data over the 3 lactations cycles approximately every 365 days. As cows regain body condition after calving at different rates, (i.e. the phase varies between cows), and cows have different total amounts of body energy loss, (i.e. the amplitude varies between cows), sinusoidal functions were associated with individual cows and allowed to vary between cows.

The model for the harmonic analysis of the data was:

$$y_i = a + bT + c_i(Sin\frac{2\pi T}{365}) + d_i(Cos\frac{2\pi T}{365}) + e_i$$

where y_i = energy balance for animal i on day T (either EB1 or EB2), T = days since first calving, a and b are fixed regression coefficients which cater for a trend over time, c_i and d_i are the random regression coefficients and e_i = error term for animal i.

4.4 RESULTS

Table 4.1 gives the maximum number of observations per animal, and the mean and maximum trait values for each trait within lactation. For each lactation there was a maximum of 36 observations per animal for condition score and liveweight, 141 for feed intake and 305 for milk yield. As expected, means for all traits apart from condition score rose with increasing lactation number. Condition score mean was highest in lactation 1, and similar for lactations 2 and 3. For all traits, a significant

improvement in fit resulted when the order of the random polynomial was increased from 3 (quadratic) to 4 (cubic). All results are therefore based on the analyses that modelled the animal deviations using cubic polynomials.

Residual error variances are given in Table 4.2 for all error classes (days) for each trait in each lactation. For MY, the residual error variance increased for each class by lactation number in line with increased yield from later parity cows. For MY and FI residual error variance declined as lactation progressed whereas for LWT it declined and then increased in the last error class. In lactation 1 the residual error variance for BCS declined in early lactation and increased up to day 99. In the last measurement error class (100-305 days) it declined dramatically. In lactation 2 and 3, residual variation for BCS followed a similar pattern to the other traits although it did not decline in late lactation. Values of residual error variance found in this analysis are similar in magnitude to those obtained from a genetic analysis reported in Chapter 3 for the last 2 classes. These latter classes are the only ones that approximated to similar time periods in lactation in both analyses.

The mean animal solutions, which include the appropriate fixed effect solutions, for BCS, MY, FI and LWT for days 1 to 305 of lactations 1, 2 and 3 are given in Figures 4.1 to 4.4 respectively. Figure 4.1 shows clearly that the reduction in BCS as lactation progresses is less severe in first lactation than in later lactations, and is commensurate with the lower yield, feed intake and liveweight exhibited by first lactation cows. The curves for LWT (Figure 4.4) suggest that an increase in body weight in lactation 1 occurs even from the start of lactation although the animal is losing body condition (Figure 4.1). This also occurs in later lactations but in successive lactations there is a more pronounced loss of total liveweight that includes condition loss in early lactation.

The mean energy balance of all cows for 3 lactations, using average values of milk and feed energy, is given in Figure 4.5 for EB1 and Figure 4.6 for EB2. Cumulative energy balance using EB2 is given in Figure 4.7. When using the milk component and feed analysis concurrent with recording time, the mean energy balance is given in Figures 4.8 and 4.9 for EB1 and EB2 respectively. The less smooth appearance of Figures 4.8 and 4.9 compared to Figures 4.5 and 4.6 is because Figures 4.8 and 4.9 have

energy balance calculated from daily solutions that are smoothed by the process of calculation (random regressions), and feed and milk analysis that vary weekly. Figure 8 is therefore likely to be the most accurate description of energy balance over 3 lactations. Figure 4.9 is erratic because the prediction of body lipid relies in part on gut fill which in turn relies on feed composition. Since feed composition analysis is conducted weekly, the estimate of daily gut fill and hence body lipid is more variable.

Table 4.3 gives correlations between energy balance estimates across lactations for selected days in milk. For EB1 correlations were generally moderate, particularly in mid-lactation, and varied from 0.21 (between lactations 1 and 3, day 7) and 0.66 (between lactations 1 and 2, day 120). For EB2, correlations were lower and ranged from 0.01 to 0.44. For cumulative EB2, correlations were low to moderate between lactations 1 and 2 but low between lactations 1 and 3 and 2 and 3.

An initial analysis of both EB1 and EB2, fitting only the mean gave a base model against which I could test the improvement in the goodness of fit when the trend line and sinusoidal functions were added to the model. For EB1, the inclusion of an overall trend line resulted in no significant improvement in fit. However, for EB2 the trend line removed a significant but small proportion (4%) of the variation. For both energy balance traits, the addition to the model of the sinusoidal functions resulted in a significant improvement in fit but with only 45% of the variation in EB1 and 40% in EB2 being accounted for. The fitted sin/cosine curve for all cows for 3 lactations using EB1 is given in figure 4.10.

4.5 DISCUSSION

In this study, in order to avoid the effects of pregnancy, initially the dataset consisted only of days 1 to 250 of lactation. This led to biologically non-sensible curves, particularly in the later stages of lactation. These were eliminated, as far as can be seen, by the use of complete datasets that span the entire period of observation. This confirms the findings of Pool et al. (2000) who concluded that random regression models did not predict the trajectory of the curve well unless all data relevant to the trajectory were used.

The condition scoring method of Lowman et al. (1976) uses a scale of 0 to 5 for cows that may vary in weight. Therefore, BCS predicts body lipid in a proportionate manner and so body lipid estimation is sensitive to prediction or measurement of body weight. In the formula used in this study, body lipid is predicted from empty body weight which is itself dependant on unbiased estimates of gut fill. Towards the end of gestation, the conceptus accounts for an increasingly large amount of body weight and may affect gut fill. Therefore, the conceptus must be properly accounted for in order to minimise error in prediction of body lipid using BCS and empty body weight. In this study the predicted weight of conceptus was subtracted from body weight before EB2 calculation. Energetic consumption by the conceptus was ignored but this would only have a small effect on EB1 calculation.

The effect of pregnancy on the individual traits was ignored in this study since the data were obtained from block-calving cows. All cows used in this study were within 4 months of calving of each other and were at approximately the same stage of lactation when pregnant. Therefore, the interaction between stage of lactation and gestation was assumed to be the same for all cows leading to no bias. Olori et al (1997) showed that yield was significantly reduced after the fifth month of gestation but that yield was only reduced by more than 1kg milk/day after 6 months of gestation. However, their study reported only the effects of pregnancy on milk yield and its components. It would be useful to know if there are significant effects of pregnancy on other traits, such as feed intake and particularly on body energy state. Of relevance to this study would be any 3-way interaction of day of lactation, current or previous body energy state and day of pregnancy. This would provide information on the genetic control of nutrient partitioning in animals of different energy status when those animals depart from their 'preferred' energy status as defined by their genetic merit for body energy at that stage of lactation (Jones et al., 1999).

It has been reported that *post partum* reproductive activity may only resume once the nadir of negative energy balance has been reached (Butler and Smith 1989, De Vries et al 1999, Veerkamp et al 2000), indicating that the rate of return to positive energy balance may be a useful indicator of resumption of reproductive activity and, by implication, possibly a useful selection objective. In this study, using EB1, cows returned to positive energy balance at days 72, 75 and 95 in lactations 1, 2 and 3 respectively. Using body state changes as an indicator (EB2) return to positive energy balance was at days 77, 83 and 73 for lactations 1, 2 and 3. This discrepancy between the methods for calculating

energy balance might be due to the inadequacy of the formulae to predict body lipid content from BCS observations, the impact of estimation of gut fill on the prediction of body lipid from BCS observations, bias in the observation of BCS in different parity animals, inaccuracies in the estimation of dietary energy content, inaccuracies in the estimation of milk energy or maintenance energy output or a combination of these. It would be useful for future research in this area to have revised values for the relationship between body lipid content and BCS observations in modern dairy cows of different weight, stage of lactation, yield level and conformation. This would enable more precise use of BCS observations for farm management purposes and for research where energy balance is needed.

The rate of body energy loss and gain relative to the start of each lactation appears to change as lactation number increases (Figure 4.7). In the first lactation there will be a component of lipid free growth that will require nutrients and increase the weight of the animal. This may slow down the apparent accretion of body fat since ingested energy will be partitioned to growth rather than deposited in fat depots that are measured by BCS.

The correlation between energy balance on the same day of lactation in different parities is an indication of how accurately energy balance calculated from data gathered in one lactation predicts the subsequent lactation energy balance. The correlations between days in successive lactations change in their profile across lactation (Table 4.3). For EB1, correlations were lower at the beginning of lactation, rose to peak at around day 150 then dropped slightly as lactation progressed. This peak in correlation corresponds approximately to the point of minimum condition score and may indicate that minimum condition score is less dependant on management or environment than is early or late lactation condition score when yields are lower. For EB2 the highest correlation occurred around 90 days but followed a similar pattern as EB1.

Changes in energy balance over the lifetime of a cow may be a useful future selection objective since there are genetic differences in energy balance profiles between bull daughter groups in their first lactation as seen in Chapter 3. A preliminary investigation indicated that lifetime energy balance may be modelled with low accuracy using sinusoidal functions. The parameters of the curves are useful since they have a biological interpretation. The phase relates to the period from calving to return to

positive energy balance and the amplitude relates to the degree of body energy loss (and recovery). Clearly, a declining amplitude over successive lactations means the cow is losing body energy over time and eventually may be compromised due to insufficient body energy reserves.

Here I used first order sinusoidal functions to model the periodic fluctuations over three lactations in an attempt to model energy balance over three lactations as a continuous trait even though the measurements do not span the dry period between lactations. I fitted a single sine and cosine function that did not produce a perfect fit. The lack of fit was associated with the fact that whilst the curve of the underlying biological process was cyclic, its shape was not symmetrical or exactly sinusoidal as there are differences in slope for the ascending and descending phases of the curve. Fitting a sine/cosine function creates a symmetrical curve and smooth continuum between lactation and dry period when the trait may in fact be discontinuous. Adding further sine and cosine terms with higher frequencies did not successfully remove this lack of fit. On the contrary, although with the addition of higher order sine and cosine terms the fit improved, the fitted curve became 'ripply' in appearance. A further complication is the lack of data throughout the dry period. Additional data on traits affecting energy balance collected during the dry period should enable us to identify a more suitable function and improve the fit.

A more detailed analysis is warranted in order to refine the fit of the curve and a possible method of achieving this is to use circular splines. These are smoothing splines constrained by boundary conditions so that in the interval (a,b) the value at a is equal to the value at b. Analysis using circular splines is the same as harmonic analysis except that the higher frequency terms are given a lower weighting, resulting in a smooth curve. Although splines allow flexibility in the shape of the curve (White et al., 1999) the inclusion of these higher frequency terms makes it difficult to attribute any biological meaning to the coefficients of the curve. A biological interpretation of the coefficients is useful in that it allows us to make meaningful associations between them and other characteristics of importance, such as longevity, health and reproductive success.

In this study, weekly milk sample analysis and feed analysis was available and so EB1 and EB2 were calculated using average values (Figures 4.5 and 4.6) and actual values for each cow for each day (Figures 4.8 and 4.9). This comparison was made to enable an assessment of the potential use of national measures of energy balance derived from linear type traits, condition score and average values of milk and feed energy. The similarity in shape of these two sets of graphs demonstrates that on average, a single lactation value for feed energy and milk energy can be used when estimating average bull daughters' energy balance. This is important if EB2 is used to calculate energy balance from national data since the estimation of empty body weight depends in part on an estimation of gut fill which itself depends on estimation of feed analysis of digestibility.

A notable difference between EB1 and EB2 in both sets of graphs (Figures 4.5 and 4.6 and Figures 4.8 and 4.9) is that the rate of return to positive energy balance is lower for EB2. This would imply a lag between the animals 'true' energy state derived from estimates of energy flux using feed energy intake and milk energy output and its energy state predicted from body fat changes. An alternative suggestion is that body fat is being mobilised from fat stores assessed using BCS and then retained within the body. This repartitioning of nutrients may be to support internal organs associated with an increased metabolic activity and lactation.

Figures 4.8 and 4.9 also demonstrate more clearly the harmonic nature of the energy balance curve across lactations. At the end of each lactation the curve tends towards zero energy balance as the animal approaches its desired energetic state. However, these data do not contain measurements taken during the dry period and therefore curve fitting is more difficult. Future experimentation to record appropriate measures through the dry period on individual cows would enable verification of the usefulness of fitting sinusoidal curves for energy balance throughout the animals productive life.

4.6 CONCLUSIONS

The relationship between energy balance in the first 3 lactations is likely to be more complex than a simple linear function but the profile of energy balance over the first 3 lactations may be a useful selection criteria in a multi-trait index. Energy balance profile over lactations 1 to 3 can only be

modelled with low to moderate accuracy using sinusoidal functions. This is due to the symmetrical nature of the function. Work is required to identify a better function relating to the underlying biological processes associated with energy balance over three lactations.

Figure 4.1. Least square mean phenotypic values by day of lactation for Condition Score

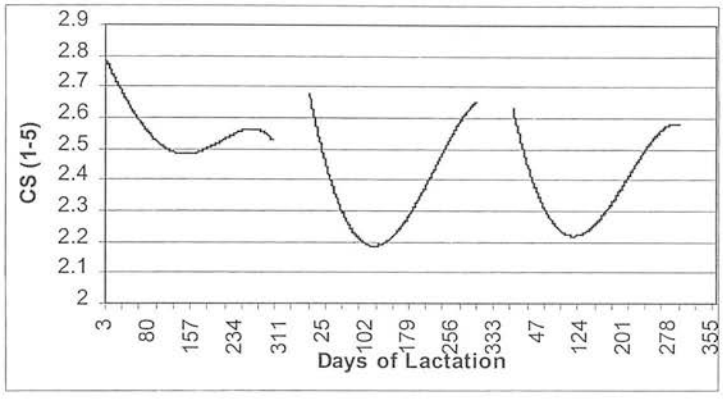


Figure 4.2. Least square mean phenotypic values by day of lactation for milk yield

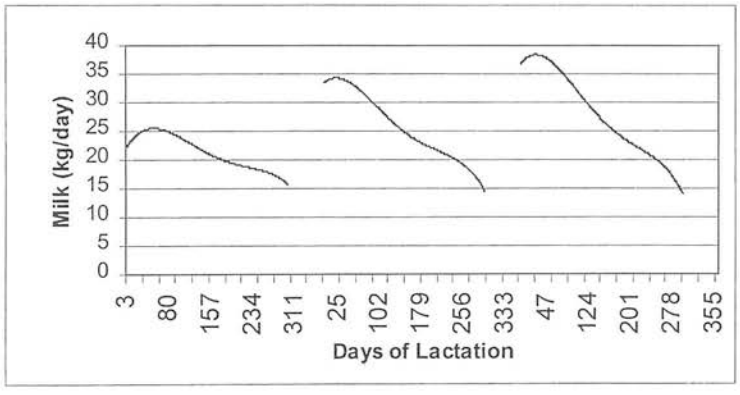


Figure 4.3. Least square mean phenotypic values by day of lactation for daily fresh feed intake

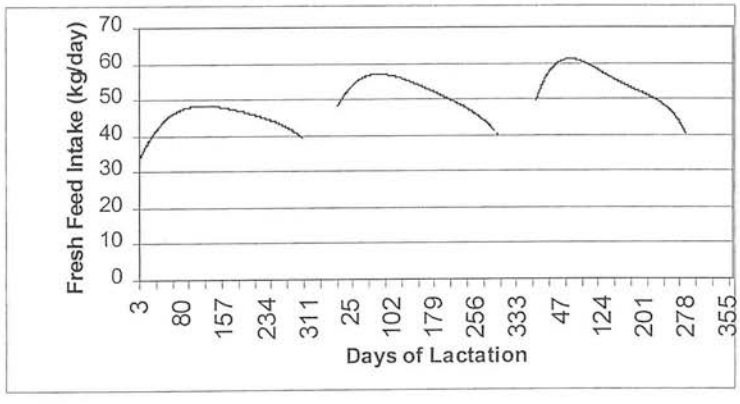


Figure 4.4. Least square mean phenotypic values by day of lactation for liveweight

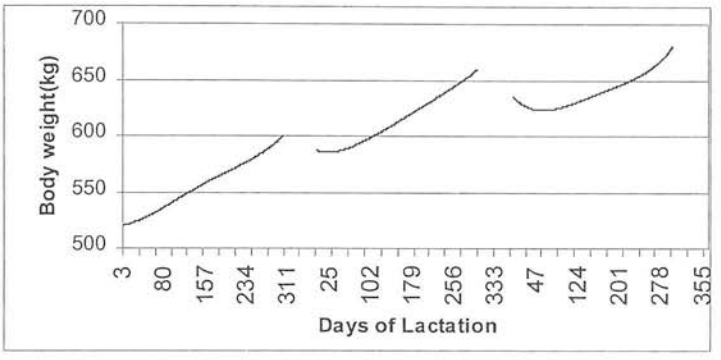


Table 4.1. Number of observations per animal (max obs.), mean, minimum and maximum for all observations for each trait for each lactation.

Trait	Lactation	Max obs. per animal	Mean	Min	Max
Milk Yield (kg/d)	1	305	21.2	3.6	52.0
	2	305	25.5	3.1	58.4
	3	305	27.6	3.1	61.7
Feed intake (fresh weight)	1	141	44.7	5.0	80.0
(kg/d)	2	141	51.9	7.3	90.0
	3	141	54.3	5.2	90.0
Condition score	1	36	2.56	1.0	4.0
	2	36	2.38	0.5	4.5
	3	36	2.39	0.75	4.75
Liveweight (kg)	1	36	557	395	710
	2	36	616	415	805
	3	36	641	460	870

Table 4.2. Residual error variance for each trait for each lactation (Lactations 1,2,3=L1,L2,L3) by measurement error class (days). Figures given for Condition Score are multiplied by 100.

	Milk Yield (kg^2)			Feed Intake (kg^2)			Condition Score (*100)			Liveweight (kg^2)		
Days	L1	L2	L3	L1	L2	L3	L1	L2	L3	L1	L2	L3
1-6	34.8	63.9	80.1	272.2	207.4	121.1	1.18	2.22	1.37	712	378	548
7-9	16.8	33.6	42.2	76.0	50.7	39.4	0.58	2.26	1.54	157	216	372
10-12	8.9	15.7	23.8	41.7	40.8	37.7	0.37	1.02	1.16	325	262	139
13-15	3.9	9.9	14.1	38.7	16.8	24.0	0.42	0.77	1.67	164	63	176
16-29	2.6	5.7	8.6	17.9	19.0	24.5	0.81	0.66	0.94	131	118	158
30-99	3.2	4.6	6.7	15.7	20.6	20.4	0.80	1.21	1.02	101	102	130
100-305	2.4	2.6	3.6	17.3	19.8	21.1	0.11	1.06	1.14	113	152	163

Table 4.3. Correlations between daily energy balance estimates across lactations for individual cows. Lactations 1, 2 and 3 = L1, L2 and L3 respectively.

	EB1			EB2			Cumulative EB1		
Day	L1/L2	L2/L3	L1/L3	L1/L2	L2/L3	L1/L3	L1/L2	L2/L3	L1/L3
7	0.26	0.40	0.21	0.28	0.06	0.01	0.28	0.08	0.02
14	0.28	0.41	0.23	0.31	0.08	0.02	0.29	0.08	0.02
21	0.31	0.44	0.26	0.33	0.09	0.03	0.30	0.08	0.02
28	0.34	0.46	0.29	0.35	0.11	0.05	0.31	0.08	0.02
35	0.37	0.48	0.31	0.38	0.13	0.07	0.32	0.09	0.03
42	0.40	0.51	0.34	0.40	0.15	0.08	0.33	0.10	0.03
56	0.44	0.55	0.39	0.42	0.21	0.12	0.35	0.11	0.05
70	0.48	0.58	0.42	0.38	0.23	0.16	0.37	0.13	0.06
84	0.52	0.61	0.46	0.43	0.25	0.18	0.39	0.15	0.08
98	0.55	0.64	0.49	0.38	0.20	0.20	0.40	0.17	0.10
120	0.60	0.66	0.53	0.44	0.21	0.19	0.42	0.19	0.13
150	0.65	0.66	0.53	0.39	0.17	0.16	0.43	0.22	0.16
180	0.66	0.62	0.49	0.38	0.17	0.13	0.43	0.24	0.18
210	0.63	0.60	0.45	0.30	0.18	0.09	0.44	0.24	0.19
240	0.55	0.55	0.40	0.11	0.23	0.04	0.44	0.23	0.18
270	0.33	0.37	0.31	0.05	0.23	0.03	0.41	0.21	0.16

Figure 4.5. Energy balance calculated from energy intake and expenditure (EB1).

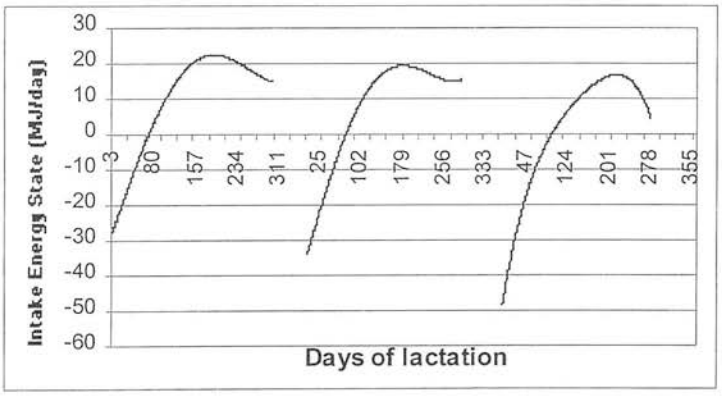


Figure 4.6. Energy balance calculated from body energy changes (EB2).

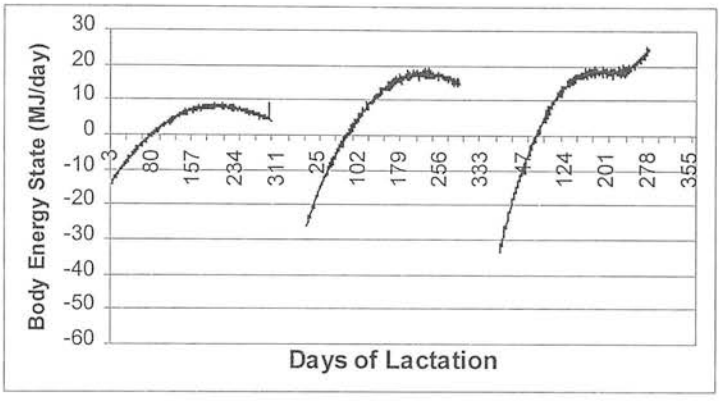


Figure 4.7. Cumulative long-term body energy state relative to body energy content at calving.

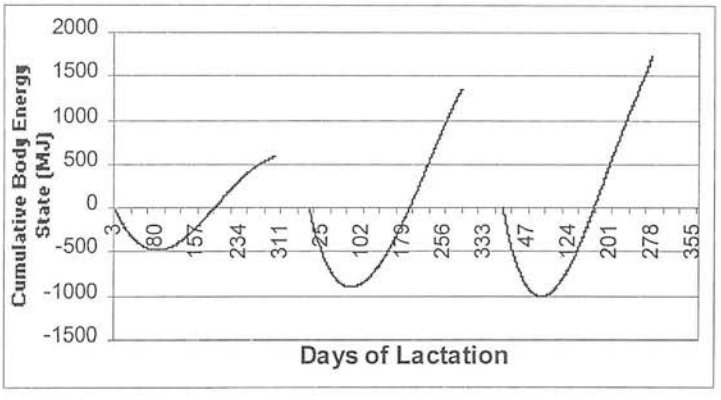


Figure 4.8. Energy balance calculated from energy intake and expenditure (EB1) and weekly milk and feed analysis.

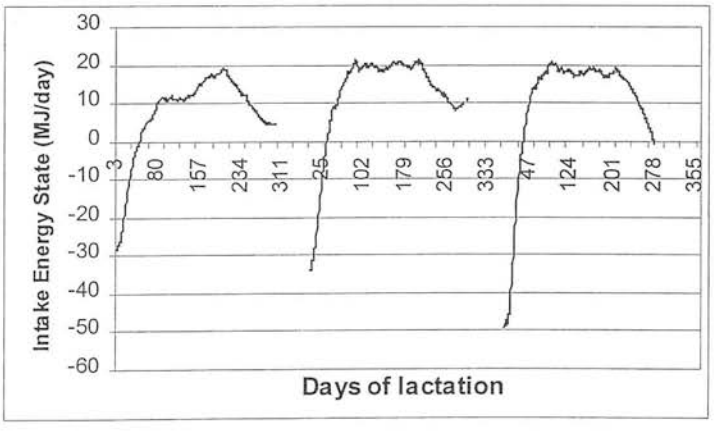


Figure 4.9. Energy balance calculated from body energy changes (EB2) and weekly milk and feed analysis.

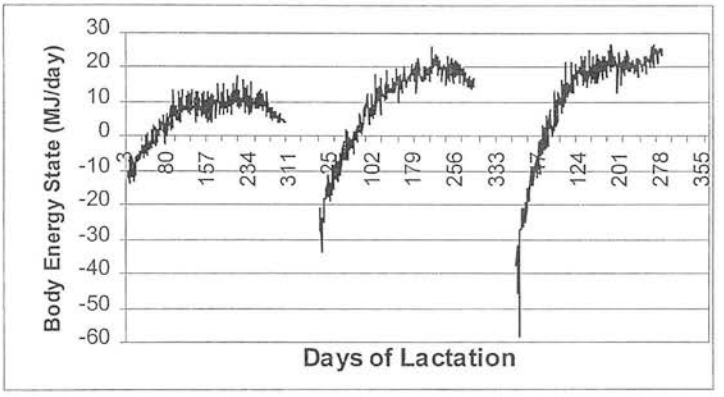
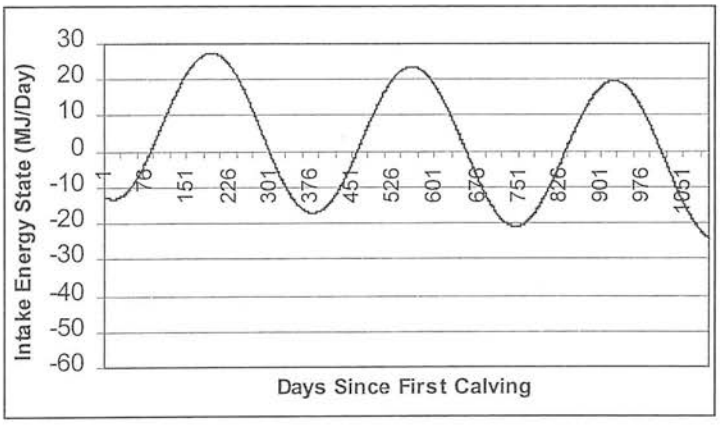


Figure 4.10. Energy balance using EB1 and sinusoidal fitting.



CHAPTER 5

Genetic Evaluations of Dairy Bulls For Daughter Energy Balance Profiles Using Linear Type Scores and Body Condition Score Analysed Using Random Regression

5.1 SUMMARY

The difference in body lipid between the start and end of lactation represents the body energy lost (or gained) in support of maintaining lactation including the non-production components of lactation. This source of energy is ignored in current genetic evaluations for production for dairy sires. The depletion and accretion of body tissue creates a pattern of body energy content over time that is, in part, under genetic control. Using random regression and field data, I modelled changes in body condition score (BCS) and liveweight, predicted from linear type traits, on first parity cows to produce daily breeding values of their sires for energy balance. These curves show that sires differ in the way their daughters lose and regain body energy throughout lactation. For all sires, the overall mean maximum daughter body energy loss was 1499 MJ (SD=144 MJ) and occurred at day 99 (SD=12.8 days) of lactation and the mean total daughter body energy loss at day 305 of lactation was 779 MJ (SD=224 MJ). In this study, the profiles of body energy loss indicate that daughters of most sires lost body energy before day 150 and then recovered body energy, whereas the daughters of a few sires continued to lose body energy through to the end of lactation. Some sires with high merit for production may have daughters with body tissue mobilisation profiles associated with poorer health and fertility leading to higher costs. A method of accounting for this cost could be to correct yield for body tissue mobilisation. Deducting kg milk from the breeding value for milk for each sire equivalent in energy content to the body energy lost, resulted in a correlation of 0.98 between the ranking of sires before and after adjustment. However, some sires changed rank by large amounts, the largest being +355 positions. Breeding values for energy balance can be calculated from single observations of BCS and linear type traits on daughters of a sire; data that can routinely be collected in national conformation assessment schemes.

Abbreviations: Liveweight (**LWT**); Body Condition Score (**BCS**); Holstein UK (**HUK**); Predicted Transmitting Ability (**PTA**); Profit Index (**PIN**); Conceptus Weight (**conW**)

5.2 INTRODUCTION

Body lipid is used by lactating mammals as a temporary energy buffer when daily energy requirement exceeds daily energy availability (Pond and Newsholme, 1999). This is particularly pronounced in early lactation when feed energy intake usually lags behind milk energy output, creating what is referred to as negative energy balance. In lactating dairy cattle, some or all of the lost body energy is replenished later in lactation. Therefore the use of body lipid in support of lactation is cyclical, corresponding to the lactation and pregnancy cycles, creating a pattern of changing body energy content over time.

Body condition scoring is a technique of appraising the fat content of the body using visual and tactile methods (Lowman et al., 1976). There is a good relationship between BCS and total body fat content (Fox et al., 1999) such that BCS is a useful management aid for dairy farmers in monitoring the nutritional and metabolic status of cows. Furthermore, BCS levels and changes in BCS are associated with the health and fertility status of the cow (Veerkamp et al., 2000; De Vries et al., 2000; Collard et al., 2000; Pryce et al., 2001), so BCS is an obvious target for potential selection indices. Selection for yield alone has resulted in cows that have a lower BCS than cows of average genetic merit for production (Pryce et al., 1999). Using random regression techniques of analysis on field data measured at different times but only once on each animal, Jones et al. (1999) demonstrated that changes in BCS throughout lactation are under genetic control and that BCS has a heritability of around 0.3. De Vries et al. (1999) reported a similar analysis with data from the Netherlands. In Chapter 3 using data from an experimental herd, I showed that BCS and LWT could be combined into an overall genetic energy balance curve for sires based on measurements of their daughters. If energy balance curves can be calculated for sires using field data collected from their daughters, the opportunity arises to explore the genetic relationship between these curves and health, fertility and survival traits. BCS is relatively easy and cheap to measure on large numbers of daughters via progeny testing and national conformation assessment schemes. Energy balance curves may provide data that could be included in a multi-trait index aimed at improving health and fertility and thereby reducing wastage from the dairy herd for both welfare and environmental reasons.

Liveweight is potentially a useful management aid (Maltz et al., 1997), yet it is not routinely recorded in UK commercial dairy herds. Liveweight can be predicted from linear type measurements and subsequent genetic evaluations for liveweight can be obtained with little loss in accuracy (Koenen and Groen, 1998). Given that BCS is recorded as part of the UK linear type assessment scheme for Holsteins, there is the opportunity to calculate sire breeding values for liveweight and condition score using large amounts of national data.

The objectives of this study were: 1) to model liveweight predicted from type traits and condition score measured in the field to obtain daily breeding values for sires; 2) to combine those daily estimates into an overall genetic energy balance profile; and 3) to compare genetic energy balance curves among sires. To do this I used random regression techniques and restricted maximum likelihood (REML) on data from lactating dairy heifers participating in the national conformation assessment scheme.

5.3 MATERIALS AND METHODS

5.3.1 *Prediction of liveweight.*

To predict liveweight from linear type traits, data for all heifers were extracted from the database of Langhill records collected since 1990. This resulted in 766 records from 444 first lactation cows. The data included records of LWT collected weekly throughout lactation and linear type records collected up to three times per lactation. Cows at Langhill were assessed for conformation as part of the national type classification scheme run by the Breed Society responsible for black and white cows in the UK (HUK) but as part of another study the animals at Langhill were classified three times annually by the same organisation. For this study the liveweight record taken closest in time to each linear type inspection was used, producing between 1 and 3 records for each cow for inspections that occurred up to 12 months after first calving. These data were analysed using a stepwise regression procedure and the REML option in Genstat (Lawes Agricultural Trust, 1993).

$$y_{it} = F_{it} + cow_i + \sum_{j=1}^{16} \beta_j x_j + e_{it} \qquad [5.1]$$

where y_{it} = liveweight recorded on cow i at time t. F_{it} represents the fixed effects of year, diet type (grazed grass or total mixed ration) and age at inspection (*aai*, grouped into 3-month classes), and the

linear covariate *pch* = percentage North American Holstein genes. β_j are the regressions of liveweight on the *j*th linear type trait, x_j, and e_{it} is an error term. The cow was included in the model as a random effect since there were repeated observations on each cow.

5.3.2 *National linear type data and condition score.*

In the national conformation assessment scheme, information on 16 linear type traits and a number of other traits including BCS are scored on a 1 to 9 scale (Brotherstone et al., 1990). Participation in the overall scheme is voluntary although once a farm is committed, every heifer on the farm at the time of the visit must be inspected. Body condition score has been included in the scheme since August 1996, based on the scoring system of Lowman et al. (1976) but adapted to be scored on a 1 to 9 scale, where 1 is the lowest level of fatness and 9 is the highest level of fatness. Data for all heifers scored since August 1996 up to March 2001 were extracted from the HUK database. This produced 240,232 records. Scores for each trait were scaled by the ratio of the individual field officer standard deviation to the mean standard deviation for all field officers, in order to standardise the range of scores for all field officers (Brotherstone et al., 1990). After records were removed for animals inspected at day 0 or after day 305 of lactation, and from sire progeny groups of less than 10, there remained 58,784 records on daughters of 1240 young sires with first crop daughters and 10 proven sires. Proven sires were included in the analysis in order to improve genetic connections within the data but these sires did not contribute to the between-sire variance component. For each of the cows in the final dataset, liveweight was predicted using equation [5.1].

Genetic and environmental variance components were estimated using a random regression sire model with the ASREML statistical package (Gilmour et al., 1998). The random regression model fitted in this study was:

$$y_{ijt} = F_{ij} + \sum_{m=0}^{f-1} \beta_m P_m(t) + \sum_{m=0}^{k-1} \alpha_{jm} P_m(t) + \varepsilon_{it}$$

where y_{ijt} is predicted LWT or BCS for daughters *i* of sire *j* at day *t* of lactation. F_{ij} represents the fixed effects of herd-year-date-of-visit interaction (a herd may be visited twice a year) and the covariates percentage North American Holstein genes (linear) and age at calving in months (linear and quadratic) for daughters *i* of sire *j*. β_m are the fixed regression coefficients, α_{jm} are the additive genetic random regression coefficients for sire *j* and ε_{it} is the error associated with day *t* of lactation. $P_m(t)$ is the m^{th}

legendre polynomial evaluated at day t of lactation and the parameters f and k are the order of the fixed and random polynomials, respectively. Legendre polynomials were used because they are easy to manipulate, have good convergence properties and, being orthogonal polynomials, correlations between coefficients are lower than between the coefficients of ordinary polynomials (Draper and Smith, 1998). Different residual errors were associated with observations over time and, based on preliminary analyses, residual error classes were defined as days of lactation as shown in Table 5.1. Within classes, residual errors were assumed to be homogeneous and between classes, residual covariances were assumed to be zero.

Based on previous genetic analyses of data from an experimental herd reported in Chapter 3, fixed regressions, which model the general shape of the curve and are common to all animals, were fitted for both traits as polynomials of order 5. Second, third and fourth order polynomials were used to model the animal effect and the goodness of fit was compared using a likelihood ratio test based on the χ^2 distribution with the number of degrees of freedom equal to the difference in the number of variance components to be estimated.

Sire predicted transmitting abilities (PTA) obtained from the analysis were used to calculate daily values for each trait on the phenotypic scale for all sires in the dataset, for all traits for days of lactation 1 to 305. Energy balance was derived using predicted body protein and lipid changes after converting all measures to energy equivalents using the effective energy system of Emmans (1994) with additional terms for the major organic components of milk. Details of the formulae used to convert to effective energy equivalents are given in Appendix A of Chapter 3.

The formula used to predict body lipid content from BCS is based on empty body weight (liveweight minus gut fill and weight of conceptus). The effects of pregnancy on the prediction of body lipid content were accounted for by modelling conceptus weight (*ConW*; foetus plus placenta plus fluid) at day p after conception using the formula from Bruce et al., (1984) which assumes a calf birth weight of 40kg.

$$\log_{10} ConW = 2.932 - 3.347e^{-0.00406*p}$$

The daily predicted weight of the conceptus was subtracted from body weight to ensure body lipid estimation was not biased upwards by the presence (weight) of conceptus. All sires were assumed to have average daughter fertility and the average daughter to be pregnant at 110 days of lactation. This expected day of conception corresponds to the average calving interval of around 390 days in the UK and *ConW* was modelled from day 110 of lactation. The effects of pregnancy and gut fill were assumed to be the same for all animals.

Dry matter intake (DMI) was predicted from the formula taken from NRC (1987)

$$DMI_i = 11.21 + (0.11 * t) - (0.0003 * t^2)$$

and was subsequently used to calculate gut fill (GF) for animal i on day t of lactation using the formula in Chapter 3, Appendix A.

$$GF_i = \mathrm{DMI_i} * (11 - (7 * \mathrm{MEC}/15))$$

where MEC is the metabolisable energy content of the feed. A value of 11.82 was derived from the mean of all total mixed ration fed at Langhill for the last 10 years and was assumed to be indicative of the average MEC of dairy cattle feed available to a cow over 1 year.

5.4 RESULTS

The following model for predicting liveweight was chosen based on the significance of the partial regression coefficients:

$$LWT = 558.43 + aai + (-0.7022 * pch) + (-7.247 * Ang) + (8.505 * CW) + (5.548 * BD) + (8.529 * Sta) + diet$$

where *aai* was 0.0, 21. 7, 34.5, 44.7, 69.2 or 68.7 for age at inspection in months of 23-25, 26-28,29-31,32-34,35-37, > 37, respectively. *pch* is percentage North American Holstein genes, *Ang* is angularity, *CW* is chest width, *BD* is body depth and *Sta* is stature. Data used to derive this formula were collected between 1990 and 2001. To generalise the formula so that it can be used outwith this period an average year of inspection solution has been included in the constant term. The variable *diet* had a value of 0 when the animals were eating grass and 34.79 when housed inside eating conserved forage. For national data it was assumed that animals were outside between months 4 and 9 (April to September).

The correlation between actual and predicted liveweight was 0.92, i.e. 85% of the variance in liveweight was accounted for using the prediction formula. Predictions of liveweight in the national population may be inferior in accuracy if the Langhill data used to derive the prediction formula are not representative of the general population. It would be useful to obtain additional data from other herds where liveweight and linear type data were available to test the formula on cows not contributing data to the formula. Since these data were not available the correlation coefficient quoted is an upper limit.

For BCS, a significant improvement in fit resulted when the order of the polynomial for the random curve was increased from 3 to 4, indicating that a polynomial of order 4 (cubic) was better able to model the data than a quadratic polynomial. For LWT, there were convergence problems using order 4 for the random curve so order 3 was used.

Residual error classes (Table 5.1) were based on earlier work described in Chapter 4 and preliminary analysis of these data. Ten classes were defined ranging in size from 1053 records (days 1-16) to 8621 records (days 60-89). Values of error variance found in this analysis are larger than those obtained from a genetic analysis of a set of experimental data reported in Chapter 3, but the data used here were taken from national records that are likely to be more variable than those from an experimental farm. Values of error variance for liveweight are similar to those reported by Koenen and Groen (1998) and for BCS are similar to those reported by Koenen et al. (2001).

The daily average sire solutions for body energy loss, relative to the start of lactation (cumulative body energy state), and for LWT and BCS are given in Figures 5.1 and 5.2. For all sires, the overall mean maximum daughter body energy loss was 1499 MJ (SD=144 MJ) and occurred at day 99 (SD=12.8 days) of lactation whilst the mean total daughter body energy loss at day 305 of lactation was 779 MJ (SD=224 MJ).

Cumulative body energy state is shown in Figure 5.3 for the two highest and two lowest sires in the dataset ranked on PIN, an index used in the UK based on milk, fat and protein weighted by their relative economic values. Predicted Transmitting Ability values were taken from the February 2002

Interbull file. These 4 sires had 23, 91, 11 and 23 daughters in the linear type dataset, respectively. These curves show that sires differ in the way their daughters lose and regain body energy throughout lactation. For the same sires, PTA's for LWT and BCS adjusted to be on the phenotypic scale are given in Figures 5.4 and 5.5, respectively.

Genetic variances and heritabilities for LWT and BCS on each day of lactation are given in Figures 5.6 and 5.7, respectively. The use of residual error classes, rather than modelling the residual error with a continuous function, creates the stepwise change in heritabilities. This is more pronounced for LWT than BCS.

For BCS, genetic correlations declined from near unity between adjacent days at the start of lactation to around 0.4 between days 1 and 110 rising to 0.6 between days 1 and 201 before declining to 0.2 between days 1 and 305 (Figure 5.8), whereas for LWT the correlations between day 1 and succeeding days reached a minimum at around day 180 and remained low thereafter (Figure 5.9). In a previous analysis of the data on the Langhill herd reported in Chapter 3, I found a similar pattern of correlations for BCS and LWT. In Chapter 3 I estimated that the genetic correlation for BCS declined from near unity between adjacent observations to 0.17 between days 7 and 247. For LWT I estimated a minimum correlation of 0.77 between days 7 and 180.

5.5 DISCUSSION

The resumption of reproductive activity in dairy cows *post partum* in most dairy cows occurs only after the nadir of negative energy balance has been reached (Butler and Smith 1989; De Vries et al 1999; Veerkamp et al., 2000). This indicates that the rate of return to positive daily energy balance may be a useful indicator of resumption of reproductive activity and, by implication, a useful selection objective to improve fertility in dairy cattle. As seen in Chapter 4, over the lifetime of the animal the replenishment of body lipid is cyclical and failure to replenish sufficient body lipid in one lactation may result in carry-over effects in subsequent lactations. Therefore, the rate of return to positive daily energy balance may also affect the total amount of body lipid replenished in one lactation that in turn may affect health and fertility traits in subsequent lactations.

Genetic variance for both traits used in this study rose abruptly towards the end of lactation. This had the effect of increasing the heritability in a similar fashion. At the minimum point of the trajectory, the heritability for LWT was about 0.30 and for BCS was about 0.25, which is similar to estimates reported elsewhere (Jones et al., 1999; Veerkamp et al., 2000). However, the rise in genetic variance at both ends of the trajectory increased the heritability to unusually high values of around 0.9 for LWT and 0.6 for BCS. An increase in genetic variance at the extremes of the trajectory could be because pregnancy effects had not been fully accounted for in this analysis or because there were limited data at these points (Pool et al., 2000). Conversely, Fischer and van der Werf (2002) found, using simulated data, that the numbers of records at the extremities had little effect on the variance. In the study reported here, conceptus weight in pregnancy was modelled to remove the additional predicted weight of the conceptus. There may be other effects not accounted for, that alter either the shape of the animal, and hence the linear type scores used to predict liveweight, or the assessment of BCS, for example, fluid retention.

The relationship between body size (or liveweight) and profitability is not clear. Sieber et al. (1988) reported that, in the US, taller cows produced more milk than shorter cows but lighter cows produced more fat corrected milk than did heavier cows in their first and later lactations. There is conflicting evidence regarding the benefit of using liveweight in a selection index since its economic value is uncertain. In New Zealand, Spelman and Garrick (1997) show that inclusion of a negative economic weight for liveweight optimises profitability in a multi-trait index and is expected to lead to a genetic reduction in liveweight of 0.19 kg/year at a selection intensity of 1.95 SD. However, BCS is a measure that predicts the proportion of liveweight (empty body weight) that is lipid, and reducing liveweight at a fixed BCS will lead to a lower total amount of body lipid in the cow. Veerkamp (1998) concluded that the relationship between feed intake, liveweight and efficiency is confounded by the relationship of yield and liveweight with body tissue mobilisation. The negative consequences of a reduction in body lipid content of cows at reduced liveweight should be considered before incorporating size or liveweight into a multi-trait index.

Mean maximum body energy loss for progeny of all sires reported in this study (1499 MJ) occurred at day 99 of lactation and is similar to but, as expected, slightly higher than that reported by Tamminga

et al. (1997) who found a total body energy loss of 1284 MJ up to day 56 of lactation. In this study, the profiles of body energy loss indicate that daughters of the majority of sires lost most body energy before day 150 and then recovered body energy, whereas a few continued to lose body energy through to the end of lactation. Current genetic evaluations for production do not account for energy contributions from body tissue mobilization, therefore some sires with high merit for production may have daughters with unacceptable body tissue mobilization profiles, leading to higher costs associated with poorer health and fertility. A method of accounting for this cost could be to correct yield for body tissue mobilization. In the energy system used in this study (Emmans, 1994), production of 1 kg milk (at 4.2% fat, 3.4% protein and 4% lactose) requires approximately 4.2 MJ effective energy. The cumulative body energy loss at day 305 of lactation was converted to the effective energy equivalent in kg milk for each sire. Using this method, the mean amount of milk accounted for by body energy loss was 189 kg milk, compared to a value of 324 kg milk quoted by Taminga et al. (1997). Deducting the body energy equivalent of kg milk from the breeding value for milk for each sire resulted in a correlation of 0.98 between the ranking of sires before and after adjustment. However, some sires changed rank by large amounts, the largest being +355 positions. The 4 sires that moved up the ranking by the most places as a result of contributing body tissue to milk production when ranked on the 'adjusted milk PTA' are given in Figure 5.10. These 4 sires had 3211, 3380, 44 and 125 daughters respectively. The 4 sires that decreased the most in the rankings are given in Figure 5.11 and these sires had 60, 20, 28 and 21 daughters, respectively. These groups of sires have clear differences in the profiles of body energy loss and gain of their daughters with those in Figure 5.10 actually gaining body energy at the end of lactation. Pryce et al. (2001) suggested that using BCS at some stages of lactation in an index could help alleviate the unfavourable effect of selection for yield on fertility. Further work is required to determine the most useful and informative parameters of the BCS curve over multiple lactations.

The strategic use of body tissue over the lifetime of the cow may be more important when assessing the cow's overall utility including costs rather than just its production, particularly since measures of utility currently used are often expressed only on a single lactation basis. The effect of a selection policy that emphasises milk yield and does not include change in body energy content on traits such as longevity, health and welfare over the lifetime of the cow has yet to be fully studied. The effect of

cyclical body tissue loss and repletion is not only seen on production but is, arguably, more important to the welfare of the cow, the consumer's view of milk production systems, the cow's potential survival and the effect of dairy farming on the environment through disposal of cull animals. Future selection indices could include indicators of body energy content as predictors of health and survival. Also, genetic evaluations for milk production in each lactation could be adjusted for body energy used in that same lactation.

5.6 CONCLUSIONS

Breeding values for energy balance can be calculated from single observations of BCS and linear type traits, data that can routinely be collected in national conformation assessment schemes. Random regression techniques of analysis provide a time oriented dimension to genetic evaluations that has a potentially valuable role in future genetic improvement programs for dairy cattle. Correcting sire milk yield PTA's for the cumulative body lipid mobilisation of daughters may provide a broader measure of utility of a sires' worth when also considering health, fertility and survival.

Table 5.1. Number of records in each of the 10 residual error classes and the corresponding error variances for condition score (CS (units^2)) and liveweight (LWT (kg^2)).

Days of Lactation	Number	Residual Error	
		CS	LWT
1-15	1053	1.64	765.8
16-29	2723	1.66	633.1
30-59	7829	1.64	589.0
60-89	8621	1.64	568.3
90-119	8336	1.67	562.9
120-149	7943	1.77	610.0
150-179	7112	1.83	628.7
180-209	6162	1.77	602.2
210-239	4851	1.84	664.7
240-305	4154	1.76	655.0

Figure 5.1. Average cumulative body energy state (MJ) for each day of lactation for all sires.

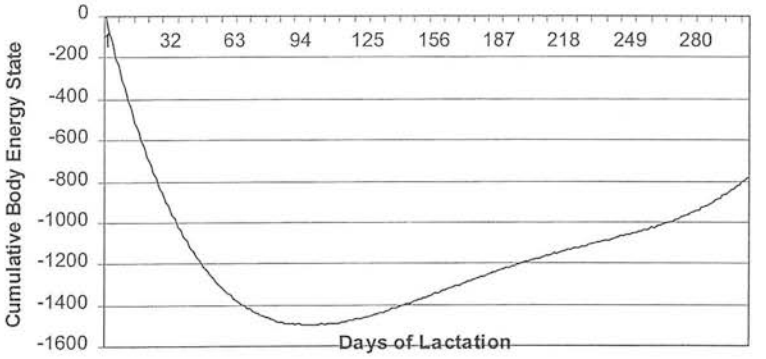


Figure 5.2. Average liveweight (kg, -□-) and BCS (units, -Δ-) for each day of lactation for all sires.

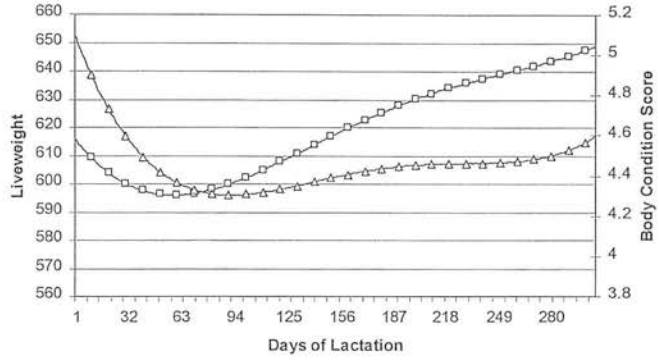


Figure 5.3. Cumulative body energy state (MJ) for the top (-x- and –ж-) and bottom (-+- and -•-) two sires ranked on profit index (PIN).

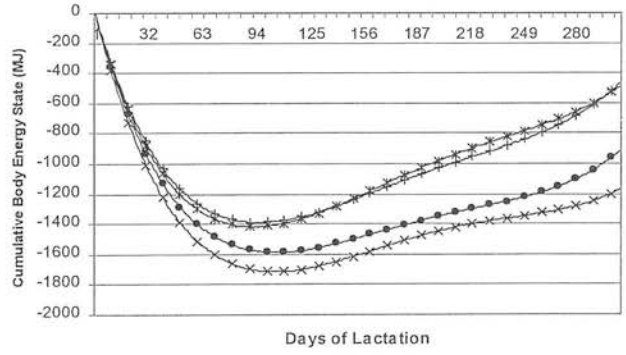


Figure 5.4. Predicted Transmitting Ability for liveweight (kg) for the top (-x- and –ж-) and bottom (-+- and -•-) two sires ranked on profit index (PIN).

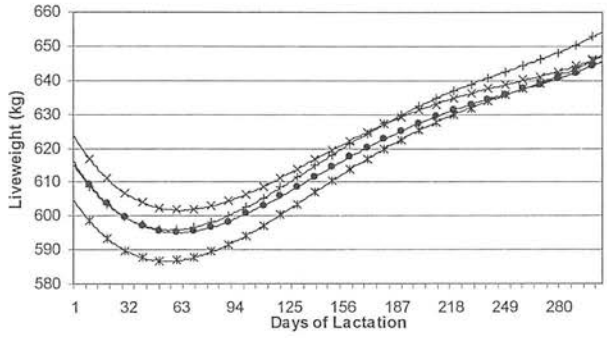


Figure 5.5. Predicted Transmitting Ability for condition score for the top (-x- and –ж-) and bottom (-+- and -•-) two sires ranked on profit index (PIN).

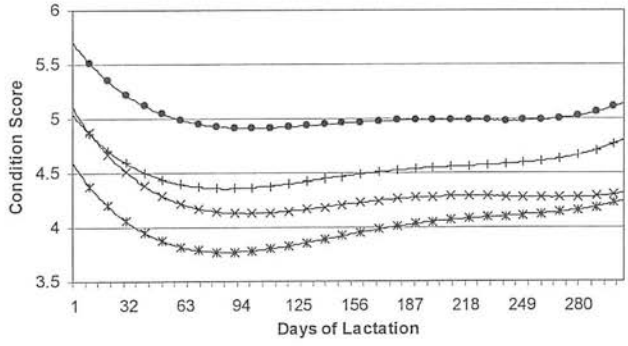


Figure 5.6. Genetic variance (▲) and heritability (x) of LWT for all sires for each day of lactation.

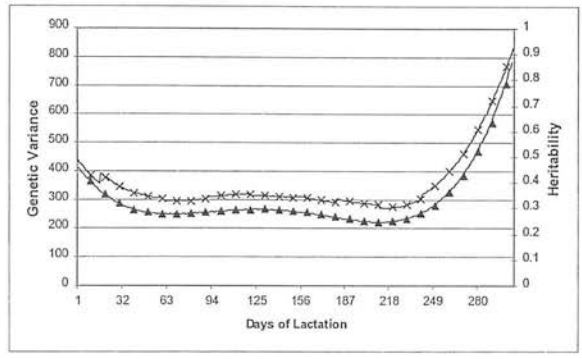


Figure 5.7. Genetic variance (▲) and heritability (x) of BCS for all sires for each day of lactation.

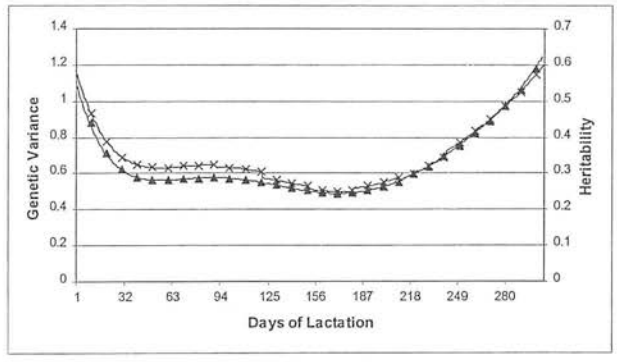


Figure 5.8. Genetic correlations of BCS at day 1 for all sires with each succeeding day of lactation.

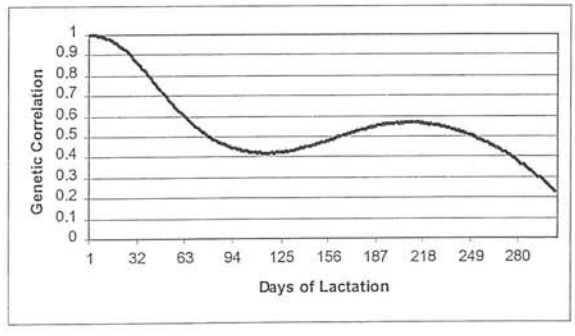


Figure 5.9. Genetic correlations of LWT at day 1 with each succeeding day of lactation for all sires.

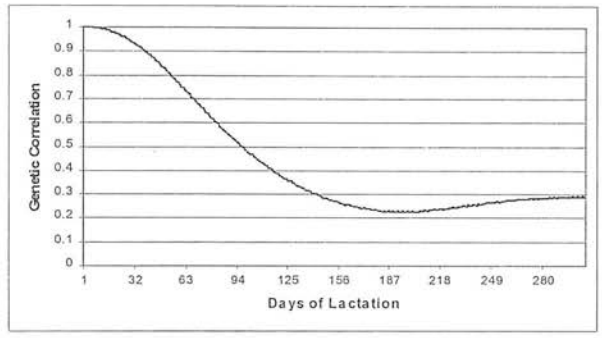


Figure 5.10. Cumulative body energy state (MJ) for the 4 sires that increased most in rank when milk accounted for by body energy was deducted from their milk PTA.

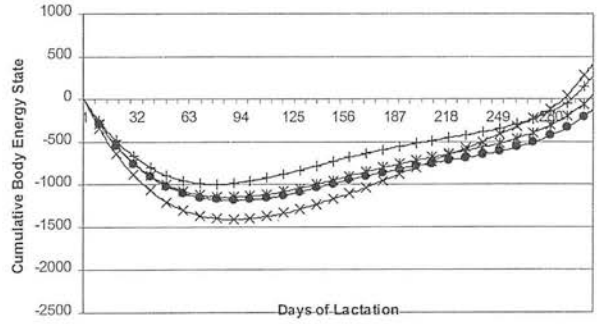
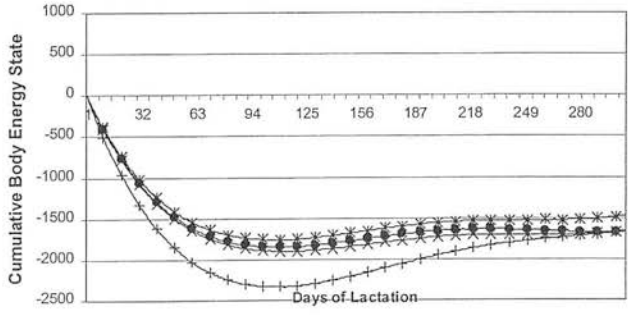


Figure 5.11. Cumulative body energy state (MJ) for the 4 sires that decreased most in rank when milk accounted for by body energy was deducted from their milk PTA.



CHAPTER 6

Predicted Energy Balance of High and Average Genetic Merit Dairy Cows Fed a High and Low Concentrate Diet Estimated Using a Multivariate Random Regression Model

6.1 SUMMARY

The economic consequences of higher involuntary culling rates due to poorer health generally leads farmers to select cows for a combination of production and survival. However, recent selection objectives that favour production to a greater extent may have led to cows that are unable to maintain high yields over many lactations. Failure to replenish body lipid lost in one lactation reduces the availability of body lipid to support subsequent lactations, potentially leading to early culling. The appropriate loss and replenishment cycle for body lipid in dairy cows is unknown and may differ for different feeding regimes. In this study, I modelled energy balance over 3 lactations using a multivariate random regression model, for cows from the Langhill Dairy Cattle Research Centre that had been selected only for maximum production (select (S)) or to remain at the National average for production (control (C)) and that were fed two diets of different energy density (high concentrate (HC) or low concentrate (LC)). Cows in the different groups differed in body condition score (BCS) and the way they lost and regained body lipid. Select cows on a LC diet lost the greatest amount of body lipid (0.54 BCS units ($p<0.005$)) after three lactations. Select cows lost more than control cows ($p<0.005$) on either diet indicating that selection for yield alone has predisposed cows to utilising body energy to support lactation on diets spanning the range used here. Select cows were heavier at first calving than control cows but lost more weight and regained more weight so that at the end of each lactation, S and C cows were of similar and not significantly different weight. There was no discernible difference in the profile of body condition score change in the first lactation for cows that lasted only one lactation compared to those lasting three lactations. However, cows that lasted only one lactation were significantly lighter at the end of the first lactation on a LC diet than those lasting three lactations. Cows use body lipid to support lactation over three lactations and the profile of that use varies according to genotype and diet.

6.2 INTRODUCTION

In high-yielding dairy cows, the peak of daily feed intake usually occurs after the peak of milk output. This disassociation in timing leads to a period in early lactation when cows cannot meet their energy requirements solely from ingested feed energy and they mobilise body energy to meet the deficit. This state is commonly known as negative energy balance (NEB) and is negatively associated with a range of health traits (Collard et al., 2000; Gillund et al., 2001; Sondergaard et al., 2002) and fertility

(Veerkamp et al., 2000; Wathes et al., 2002; Dechow et al., 2002). It can generally be considered to be undesirable not only for its direct economic cost but also for its potential effect on the health of the cow from a welfare viewpoint (Nielsen et al., 1998).

Research to identify nutritional methods of overcoming NEB is currently underway (Garnsworthy, personal communication) and phenotypic NEB could be described as an outcome state that is a result of the genetic relationship between milk yield, feed intake and body lipid content and the interaction with the management environment. This trivariate relationship between the traits, which changes as lactation progresses, also describes nutrient partitioning and the difference in partitioning priorities between animals of differing genotype for yield and on different planes of nutrition is not well documented.

Body condition score (BCS) is a technique of appraising the body lipid content of dairy cows (Lowman et al., 1976) and is used routinely in the dairy industry. It is a good predictor of total body lipid content (Fox et al., 1999) and has a heritability of around 0.30, similar to that of production (Dechow et al., 2003; Chapter 3; Jones et al., 1999). Genetic correlations between yield and feed intake suggest that the expected increase in feed intake is less than that required to cover the extra energy requirements for yield when selection is for yield alone (Veerkamp, 1998), leading to a net BCS loss. Continuing with this selection policy is likely to result in a greater loss of body condition for animals selected for yield.

These features of BCS make it a candidate for inclusion in future selection indices that incorporate a wider range of direct measures of cost and that have improved health and welfare and reduced environmental impact as part of the goal (Chapter 5). In order to incorporate body energy into selection indices, more information is required on the relationship between body energy changes in early and later productive life and how that relationship is affected by genotype and by nutrition. This will enable selection for a genotype with an appropriate lifetime body energy profile that optimises profitability consistent with consumers' expectations for animal production systems.

The objectives of this study were: 1) to calculate daily energy balance for three consecutive lactations for individual cows from the Langhill Dairy Cattle Research Centre, 2) to investigate the influence of genotype and concentrate feeding level on energy balance and 3) to investigate the possibility of using early life energy balance parameters to predict survival.

6.3 MATERIALS AND METHODS

6.3.1 *Data.*

Data were extracted for all cows in lactations 1 to 3 from the database of Langhill records collected from 1990 until July 2002. At this point, the trial to record feed intake used in this study was terminated and the dataset consisted of animals that had a range of lactations completed under the trial up to lactation 3. The data included records of milk production and milk composition, liveweight (LWT), BCS and fresh feed intake (FI) for two lines of cows. These lines have been continuously selected either for kg fat plus protein (select line (S)) or selected to remain close to the average genetic merit for fat plus protein production for all animals evaluated in the UK (control line (C)). Approximately equal numbers of S and C cows were housed together and offered either a high or a low concentrate diet in the form of a total mixed ration (TMR) either for a minimum of 26 weeks or a maximum of 38 weeks of each lactation. Animals that calved early in the calving season, which started around August each year, were kept on trial for the full 38 weeks providing that the 38 weeks of recording was finished in June of the following year. If an animal calved too late to have the full 38 weeks recorded before June, the animal was removed from the trial after 26 weeks of recording. Outside this period of recording, cows received a standard TMR when housed or they grazed grass. The diets were formulated to contain approximately 1.5 or 2.5 tonnes of concentrate per lactation for the low and high concentrate diets respectively representing a typically low and moderately high concentrate usage.

Milk yield (MY) data consisted of summed daily yield measured at morning and afternoon milking up to 305 days after calving. Aberrant records apparently caused by illness or oestrus, or milk records known to be in error were removed from the main dataset. This was assumed if the value at any milking was more than 3 standard deviations different from the mean of all other records for the same parity, feed group, genetic line and on the same day of lactation. This resulted in the removal of 1382

daily records out of 757,952 individual daily recordings from 995 different animals. Of these, only 26 animals had more than 10 daily records removed. Of the 1382 daily records removed, 600 were more than three standard deviations above the mean. From this main edited dataset, records for each of the four traits analysed (daily milk yield, condition score, liveweight and fresh feed intake) were extracted separately for all animals that had been recorded on the feed intake trial for any length of time. This produced records for 501 animals. Of these, 90 had a maximum of one lactation of feed intake data, 88 had a maximum of two lactations of data and 323 had three complete lactations of feed intake data.

Liveweight was measured and condition score assessed at the same time once each week after morning milking. Condition score was assessed by the same operator over the entire period of record collection using a 0 to 5 scale with 0.25 intervals (Lowman et al., 1976) where 0 is thin and 5 is obese. Food was available *ad libitum* and individual intakes were recorded either through Calan Broadbent gates up to 2001 or HOKO automatic feed measurement gates from 2001 to 2002. For data collected by Calan Broadbent gates, daily FI was calculated from each of four consecutive days (Monday to Thursday) of measurements of feed offered and refused. Feed offered was weighed on one morning and refusals weighed and removed the following morning. For data collected in the last year of the trial through HOKO feeders, daily FI was recorded automatically every day. Feed offered was adjusted periodically so that feed refused was around 10% of the total offered. Cows observed to habitually waste food by throwing it were removed from the trial since feed intake for these animals is biased upwards. Table 6.1 shows the number of observations for each trait for each lactation. Effective energy intake for those days where feed intake was measured was estimated using the effective energy system of Emmans (1994).

6.3.2 *Model for analysis.*

Variance component estimation was performed using the ASREML statistical package (Gilmour, 1998) with a multivariate random regression model. Since pedigree information was not included in the analysis, animal solutions are combined animal genetic and permanent environmental effects. The random regression model fitted in this study was:

$$y_{it} = F_{it} + \sum_{m=0}^{f-1} \beta_m P_m(t) + \sum_{m=0}^{k-1} \lambda_{im} P_m(t) + \varepsilon_{it}$$

where F_{it} represents fixed effects of genetic line (2 groups), feed group (2 groups), time of measurement (year and week of measurement), diet type (TMR or grass), pregnancy group (not pregnant and pregnant for up to 70, 100, 130 and continuing up to 280 days in classes of 30 days) and the covariates percentage North American Holstein genes (linear) and the difference between age at calving and mean age at calving for this lactation in months (linear and quadratic) for animal *i*. All effects were fitted within lactation except for the modelling of feed intake where records only existed for a portion of the lactation. For this trait all records were within one feed class (TMR) and so time of measurement and pregnancy class effects were fitted overall. β_m are the fixed regression coefficients, λ_{im} are the random regression coefficients associated with the animal and lactation plus its permanent environment and ε_{it} is the residual error associated with days since calving *t* in that lactation. $P_m(t)$ is the m^{th} Legendre polynomial evaluated at *t* and the parameters *f* and *k* are the order of the fixed and random polynomials respectively. Legendre polynomials were used because they are easy to manipulate, have good convergence properties and, being orthogonal polynomials, when multiplied by the regression coefficients, correlations between the resulting coefficients are lower than between the coefficients of ordinary polynomials.

The four traits analysed separately by lactation were milk yield, condition score, feed and liveweight. Residual, or measurement, errors were expected to have heterogeneous variances through the course of each lactation, with larger variances at the beginning of lactation and around peak yield. Different residual errors were therefore associated with observations over time. Based on previous analyses of similar data (Chapters 3 and 4), residual error classes were defined as days 1 to 6, 7 to 9, 10 to 12, 13 to 15, 16 to 29, 30 to 99 and 100 to 305. These classes were defined to provide sufficient records in each class in early lactation but also to produce sufficient granularity of the data at the early part of lactation when changes are greatest. Within classes, residual errors were assumed to be homogeneous and between classes, residual covariances were assumed to be zero. Fixed regressions, which model the general shape of the curve and are common to all animals, were fitted for all traits as polynomials of order five based on previous analyses of similar data (Chapter 5). Fourth order polynomials were used to model the animal genetic plus permanent environment effect.

Daily solutions for days of lactation 4 to 305 obtained from the analysis were used to calculate daily values on the phenotypic scale for all cows in the dataset, for all traits. Energy balance was derived using either daily milk yield and daily feed intake (EB1) or predicted body protein and lipid changes (EB2) after converting all measures to energy equivalents using the effective energy system of Emmans (1994). Both methods included energy used for maintenance and activity that was dependent on both feed composition and liveweight. Details of the formulae used to convert to effective energy equivalents are given in Chapter 3, Appendix A.

The method of calculating daily body lipid content relies on an estimate of gut fill predicted from feed intake and feed composition. The feed composition was analysed weekly and occasionally the change in composition was sufficient to cause a large change in predicted body lipid content from one day to the next at the boundary of the change in feed composition. Therefore, when body lipid or body protein changed by more than 1.5kg the daily change was set to be the same as the day before to smooth out large fluctuations in body energy change that were an artefact of the calculation method.

The energy required to grow the foetus was calculated from daily predicted protein and lipid retention in the foetus using formulae from ARC (1980) and was assumed to be constant for all cows. The effective energy required for foetal growth was assumed to be the same as for maternal growth since the effective energy system (Emmans, 1994) does not consider foetal growth. This adjustment affects only EB1. The effects of the weight of the conceptus (foetus plus placenta plus fluid) on the prediction of empty body weight were accounted for in part by modelling conceptus total weight using an exponential growth curve from day of conception (ARC, 1980). The parameters of this curve were adjusted to result in a weight of gravid uterus at 281 days of gestation of 71, 78 and 85kg respectively for lactations 1 to 3, to account for assumed increases in weight of 10% per lactation for this component in larger and older cows. The daily predicted weight of conceptus was subtracted from empty body weight to reduce any upwards bias on body lipid estimation by the presence of conceptus which would otherwise have affected EB2. The daily predicted weight of conceptus was assumed to be constant for all cows of the same parity.

6.4 RESULTS

There were 501 cows in the dataset that had at least one lactation with feed intake records. Where animals had at least three lactations with feed intake records there were 69 and 64 control cows in the low concentrate and high concentrate groups respectively. For the select cows there were 97 and 93 cows in the low concentrate and high concentrate groups respectively. Residual error classes were based on earlier work using a similar dataset (Chapter 4) and preliminary analysis of these data. Seven classes were defined to provide sufficient records in each class but also to allow sufficient classes of the data in early lactation where changes are greatest. Estimates of error variance (Table 6.1) found in this analysis are, as expected, very similar to those found in Chapter 4 except for feed intake in the first error variance class where they are generally lower in this study. The difference between the datasets in these two studies is that here I used all records for animals on the feed intake trial whereas in Chapter 4 only those animals having at least three lactations on the trial were included. Error variances for LWT are similar to those reported by Koenen and Groen (1998) and for BCS are similar to those reported by Koenen et al. (2001).

Correlations for EB1, EB2 and cumulative EB2 between a selection of days in each lactation for all cows that had at least three lactations of feed intake data are given in table 6.2. For daily EB1 and EB2 the correlation between successive lactations are higher than for those between lactations 1 and 3 and are variable over lactation. For cumulative EB2, correlations range from 0.37 in early lactation to 0.80 in late lactation when comparing lactations 1 and 2. For lactations 2 and 3, the correlations are higher, ranging from 0.67 in early lactation to 0.83 in late lactation. For lactations 1 and 3, the correlations are similar to those for lactations 1 and 2 and are still high, ranging from 0.31 to 0.73.

The overall mean solution, which includes the appropriate fixed effect solutions, for each day of lactation for three lactations for all cows that had at least three lactations of feed intake data are shown in Figures 6.1a to 6.1e for milk yield, fresh feed intake, liveweight and condition score respectively. These Figures are in close agreement to those reported in Chapter 4. The orthogonal polynomial coefficients and the regression coefficients required to produce daily solutions are given in Appendix B, Tables 6.3 to 6.5.

The pattern of energy balance change over lactations for EB1 is shown in Figure 6.1f and for EB2 in Figure 6.1g. These Figures are similar in shape to those reported in Chapter 4 for both EB1 and EB2 using a univariate random regression analysis but the magnitude of positive and negative energy balance is higher in this study for EB1 where I used a multivariate random regression analysis. The range of energy balance is similar to that reported by Riest et al. (2003) for animals in lactations 2 and 3.

Average daily milk yield, fresh feed intake, liveweight and condition score for all four groups of cows are given in Figures 6.2a to 6.2d respectively. As expected, the S cows on the high concentrate diet had the highest daily yield (Figure 6.2a). The S cows on the low concentrate diet produced more milk than the C cows on the high concentrate diet and the difference between these two groups was most pronounced in the third lactation. Whilst diet affected yield in both S and C cows during lactation, by the end of lactation daily milk yield was similar among S cows irrespective of diet and among C cows irrespective of diet. The S cows did, however, have higher yields at the end of lactation than the C cows.

Feed intake was greatest for S cows on the low concentrate diet (Figure 6.2b) and S cows had a higher feed intake on both diets than C cows. The difference between the groups in daily fresh feed intake was greatest in the third lactation. Select cows were also heavier by 44kg ($p < 0.005$) at the start of each lactation (Figure 6.2c) and lost more weight than C cows. All groups were of approximately equal weight at the end of each lactation. Select cows were of significantly higher BCS at the start of the first lactation ($p< 0.005$) and significantly lower BCS by day 18 of lactation 2 and day 12 of lactation 3 ($p<0.005$). Select cows lost more body condition at the end of the third lactation (0.53 BCS units and 0.46 BCS units) than C cows for high and low concentrate diets respectively ($p<0.005$). Select cows on a low concentrate diet had the lowest BCS at the end of the third lactation and had lost the greatest amount of body condition (0.54 BCS units).

The average daily energy balance (EB1) is given in Figure 6.2e. Cows have a NEB of about 50, 75 and 125 MJ day in early lactation in lactations 1, 2 and 3 respectively. Figure 2f shows the cumulative body energy content (lipid and protein) from first calving derived from EB2. The effect of diet was significant for both genetic groups and all groups became significantly different for cumulative body

energy content by day 15 of lactation 1. However, C cows were not significantly different from each other after day 45 of lactation 1. Select cows had significantly less ($p<0.005$) body energy than C cows throughout the 3 lactations and S cows on a high concentrate diet had significantly less ($p<0.005$) body energy than S cows on a low concentrate diet after day 6 and throughout the 3 lactations. The biggest difference in body energy content at the end of the third lactation was 3206 MJ and occurred between the S and C cows on the low concentrate diet.

The culling policy of this experimental herd is that cows are kept on trial for as long as possible once they start. Furthermore, the trial was designed to have as many heifer records as possible and so preference was given to introducing heifers to the trial rather than keeping older cows. Therefore for select cows only, Figures 6.3a, 6.3b and 6.3c show the profiles for liveweight, condition score and cumulative body energy state that survived 1, 2 or 3 lactations on the trial whilst receiving a low concentrate diet. Figures 6.4a, 6.4b and 6.4c show the same profiles for cows receiving a high concentrate diet.

6.5 DISCUSSION

This study is a more detailed analysis of energy balance over three lactations for two different genotypes on two different diets than that reported in Coffey et al. (2002). This study used a multivariate random regression model that allowed incomplete lactations and records for animals not having 3 lactations of feed intake data to be used in the analysis. Results presented here demonstrate that a selection objective emphasising production alone results in cows that have significantly less body energy (Figure 6.2f) although they are the same weight (Figure 6.2c) predominantly because they have less body lipid at the end of 3 lactations (Figure 6.2d). This gradual erosion of body energy stores may be of concern from a health, welfare and profitability viewpoint.

As expected, the select cows gave more milk on both the high and low concentrate diets (Figure 6.2a) and had a higher fresh feed intake on the low concentrate diet, particularly in early lactation (Figure 6.2b). The select cows on the high concentrate diet appeared to have a more persistent feed intake curve because the feed intake at the end of lactation was similar to that of the low concentrate group. The select cows were heavier at calving in all 3 lactations but lost more weight than the control cows

on both diets (Figure 6.2c) in all three lactations. All cows were similar in weight at day 305 of each lactation. Apart from the control cows on a high concentrate diet, all cows continued to lose BCS throughout the 3 lactations with the select cows on the high concentrate diet having lost the most by the end of the third lactation. The magnitude of maximum BCS loss was similar for lactations 2 and 3 and both had greater loss than lactation 1.

The change in shape of the NEB curve in lactation 3 may be explained by the alteration in shape of milk production curves for these animals. The milk production peak is reached much earlier in successive lactations (Figure 6.1a) but the rise in feed intake is similar in each lactation (Figure 6.1b). Therefore, in the absence of a rise in the rate of increase in feed intake over lactations, multiparous animals will be in increasing NEB in early lactation due mostly to their more rapid output of milk.

Both genetic lines of cows on the low concentrate diet typically have a later return to positive energy balance than cows on the high concentrate diet. The select cows on the low concentrate diet were in the lowest energy balance state (i.e. most negative) throughout the 3 lactations (Figure 6.2e). This is also evident from Figure 6.2f which shows the predicted cumulative body energy content (lipid and protein). Select animals on both diets accumulate the least amount of energy over their lifetimes and at the end of the third lactation have approximately 3200 MJ less body energy than the control cows even though they are a similar weight. This is because they have significantly less body lipid (Figure 6.2d).

Daily energy balance calculated from feed intake and milk output (EB1, Figure 6.1e) suggests cows return to positive energy balance faster after each calving than when estimated from body lipid changes (EB2, Figure 6.1f). Whilst in part this may be explained by BCS being an incomplete assessment of body lipid content or a delay in subcutaneous body lipid being mobilised, an additional explanation might be that the calculation of EB1 is biased upwards. There is an assumption that all food recorded as eaten is actually consumed by the cow whereas, in reality, some is wasted. Therefore actual feed intake is lower than that recorded. Furthermore, the digestibility of feed in this study is assumed to be linear across the range of feed intakes measured and constant throughout lactation. If this is not so and digestibility of feed reduces at higher intake rates or is lower soon after calving, then

EB1 would be affected both in early lactation and at the peaks of feed intake. Digestibility is assumed to be lower by 1.8% per multiple of maintenance energy intake (ARC. 1980). In this study cows were consuming approximately 3 times maintenance requirements at peak intake and a 5.4% reduction in digestibility at this time would equate to a reduction of energy intake and hence EB1 of about 10MJ.

At the boundary in time when diet composition changes, there is a large effect on the prediction of gut fill and hence body lipid content, leading to aberrant values for body energy change on a daily basis. Future work should attempt to smooth these values to create a smoother transition from one stage to the next. A method to do this would be to convert all inputs and outputs to energy equivalents before analysis using a random regression model and use the smoothed values to calculate energy balance. This technique of analysis was employed by Shwager-Suter et al. (1991) who used the Net Energy system and polynomials to smooth the resulting energy balance. In this study, I chose not to conduct this type of analysis because fixed effects were thought to affect each trait differently. In particular, pregnancy effects operate at the individual animal level and the effects of pregnancy on energy balance vary throughout lactation. The fixed effects of pregnancy stage were added back to the daily solution to adjust energy balance at the phenotypic level for the effect of pregnancy at each stage of pregnancy for each cow.

Adjustments for the effects of pregnancy on body weight and energy used by conceptus were considered separately for EB1 and EB2. For EB1, the energy utilised by the growing foetus was subtracted from energy intake since it is an energetic cost to the cow. However, the energy required for the gravid uterus was not included since this is retained by the cow post-partum and returns to the nutrient pool. The energy requirement of the foetus is relatively small compared to daily energy requirements for yield. At day 281 of pregnancy, the foetus is utilising around 5MJ of effective energy per day assuming that foetal utilisation of energy is the same as maternal usage. This is likely to be an underestimate since the foetus uses maternal amino acids as an energy source creating additional heat to be lost by the mother. For EB2, the whole conceptus predicted weight was subtracted from empty body weight and then body lipid content calculated from the remainder.

The effect of NEB on reproduction has been studied extensively. Taylor et al. (2003) found a significant and unfavourable relationship between NEB and delayed ovulation in primiparous high yielding cows. Veerkamp et al. (2000) demonstrated that the commencement of luteal activity (CLA) predicted from milk progesterone levels was unfavourably correlated to NEB and suggested that a selection index containing feed intake would allow selection for yield at a constant CLA. However, Riest et al. (2003) have shown that resumption of ovulation post partum was not affected by NEB but conception rate was. These authors suggest that NEB mediates an effect on reproduction at the conception stage due to a change in the physiological state of the cow with regard to metabolic hormones such as thyroxine and steroid precursors such as cholesterol. This is supported by a meta-analysis by Lopez-Gatius et al. (2003) who suggest that, within the normal range of body energy gain and loss, follicular activity appears to be unaffected by NEB. However, they too note that days open increase when NEB is large.

The future availability of integrated management systems will benefit from body energy measures and the use of statistical techniques of analysis that span time, such as random regressions, will allow for integration in three dimensions – genotype x environment x time. However, the measurement of traits, other than production and SCC, in dairy cows later in productive life is not widely practised on-farm because it is expensive and early life single point measurements are usually used as predictors. To make use of profiles some early life parameters of profile shape must be used as predictors of later life profile shape or an automated system of collection of pertinent data developed to enable routine collection of later life data. Wathes et al. (2002) explore the possibilities of an integrated management system that collects biochemical as well as physical data to use in an automated metabolic monitoring system to assist in reproductive management.

There is an intimate relationship between body energy content, milk yield and profitability in dairy cows in part due to the cost of producing the body energy and in part due to the effect that changes in body energy have on traits such as health and fertility. This suggests that body energy, or a parameter of its change, is a suitable candidate for inclusion in future selection indices. Incorporating body energy into an overall index would enable the selection of cows that have a suitable profile of body energy content at a given yield level. Selecting concurrently for yield and reduced body lipid loss in

early lactation is, in effect, selecting for increased energy intake. This is predicted to improve health and welfare of cows but also has an economic cost. Veerkamp and Brotherstone (1997) suggest that a restricted index in which BCS is maintained at its (then) current level is predicted to reduce overall economic genetic gain by 5%. The most appropriate combination of yield and body lipid loss must be determined and an economic value calculated before it can be used in an overall profit index. This is worthy of future investigation.

6.6 CONCLUSIONS

Selection for yield alone has led to cows that mobilise more of their body energy in early lactation and cows that do not replenish all lost body lipid throughout their productive life. For select cows, this results in a net loss of body lipid that is greater when they are fed a low concentrate diet. These findings have implications for management systems required for cows selected for yield alone or for selection objectives for cows that must be kept in a low concentrate management environment. Future selection indices could include body lipid content in an attempt to limit BCS loss, NEB and the concomitant health and fertility problems.

Table 6.1. Number of records in each of the 7 residual error classes and the corresponding residual error variances (REV) for milk (kg^2), fresh feed intake (FI kg^2), body condition score (BCS $units^2$ * 100) and liveweight (LWT kg^2).

Days of Lactation	Milk		Feed Intake		Body Condition Score		Liveweight	
	Records	REV	Records	REV	Records	REV	Records	REV
Lactation 1								
1-6	938	34.7	171	126.6	144	1.48	154	599.3
7-9	1238	17.7	477	96.8	176	1.08	179	365.8
10-12	1288	9.6	590	49.3	183	1.17	186	322.6
13-15	1308	5.5	655	31.3	201	0.59	205	135.0
16-29	6339	3.3	3406	15.9	894	1.15	905	152.1
30-99	33026	3.5	18789	16.9	4583	0.88	4694	111.1
100-305	94901	2.9	37655	17.0	12031	1.04	12343	116.6
Lactation 2								
1-6	688	65.8	141	138.2	116	3.02	119	334.8
7-9	1151	33.1	429	55.4	153	3.31	157	349.2
10-12	1168	15.0	494	37.6	161	1.65	162	239.3
13-15	1190	8.8	482	20.6	145	2.07	148	142.8
16-29	5537	5.6	2534	19.7	719	0.76	746	162.7
30-99	27329	5.6	13282	21.8	3628	1.04	3723	119.1
100-305	75217	3.4	24856	25.3	9413	1.05	9609	134.0
Lactation 3								
1-6	491	79.5	101	117.1	100	2.08	102	541.8
7-9	892	43.5	285	45.4	110	2.31	113	571.0
10-12	911	19.3	324	41.7	123	1.21	128	248.5
13-15	909	14.1	353	25.4	116	1.95	118	171.2
16-29	4329	10.5	1723	28.5	572	0.92	585	203.5
30-99	21052	8.7	8652	24.3	2736	1.05	2777	141.1
100-305	55909	4.5	16170	27.4	7138	0.94	7188	154.7

Table 6.2. Correlations between energy balance measures on a selection of days in lactation across lactations for all animals with at least three lactations of recorded feed intake.

	EB1			EB2			Cumulative EB2		
day	L1/L2	L2/L3	L1/L3	L1/L2	L2/L3	L1/L3	L1/L2	L2/L3	L1/L3
7	0.13	-0.03	-0.01	0.08	0.04	0.04	0.37	0.67	0.31
14	0.22	0.11	0.07	-0.01	0.05	-0.04	0.58	0.71	0.51
21	0.24	0.08	0.08	0.14	-0.03	0.09	0.65	0.74	0.55
28	0.24	0.13	0.08	0.26	0.25	0.23	0.68	0.76	0.57
35	0.21	0.13	0.07	0.34	0.32	0.23	0.70	0.78	0.59
42	0.21	0.12	0.05	0.31	0.32	0.26	0.71	0.79	0.60
49	0.15	0.12	0.08	0.12	0.27	0.12	0.72	0.79	0.61
56	0.18	0.17	0.11	0.43	0.42	0.30	0.73	0.80	0.62
63	0.18	0.20	0.11	0.34	0.31	0.28	0.74	0.80	0.63
70	0.23	0.21	0.15	0.14	0.24	-0.05	0.75	0.80	0.64
77	0.22	0.20	0.17	0.31	0.30	0.22	0.76	0.81	0.64
84	0.17	0.23	0.17	0.04	0.07	0.02	0.76	0.81	0.65
91	0.19	0.26	0.21	0.20	0.16	0.21	0.77	0.81	0.66
98	0.23	0.27	0.20	0.36	0.24	0.31	0.78	0.81	0.67
120	0.22	0.27	0.17	0.00	0.01	-0.02	0.79	0.81	0.68
150	0.30	0.28	0.16	0.12	0.41	0.21	0.80	0.81	0.71
180	0.31	0.32	0.26	0.18	0.31	0.21	0.79	0.81	0.72
210	0.28	0.40	0.18	0.21	0.28	0.12	0.79	0.82	0.72
240	0.26	0.40	0.27	0.15	0.22	0.03	0.78	0.83	0.73

Figure 6.1a. Least squares mean daily milk yield (kg) for three lactations for all cows.

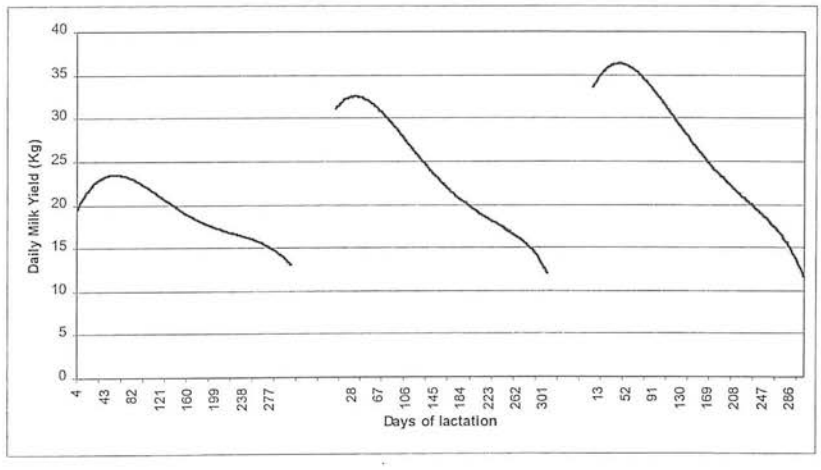


Figure 6.1b. Least squares mean daily fresh feed intake (kg) for three lactations for all cows.

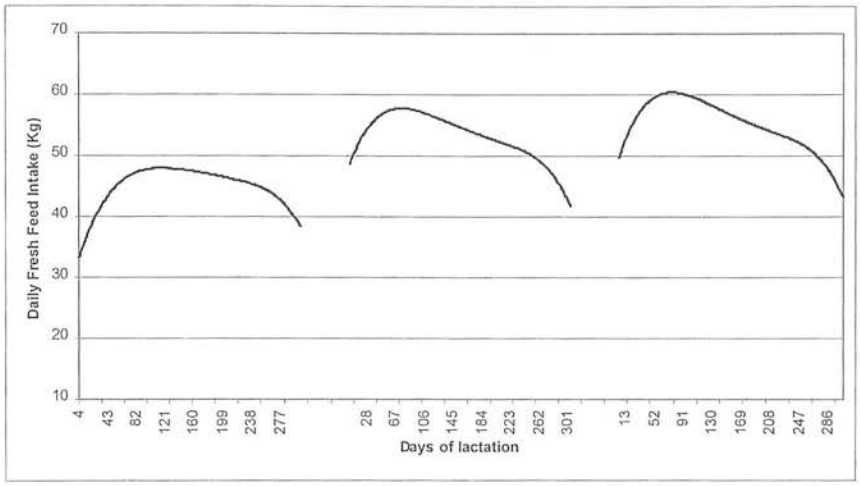


Figure 6.1c. Least squares mean liveweight (kg) for three lactations for all cows.

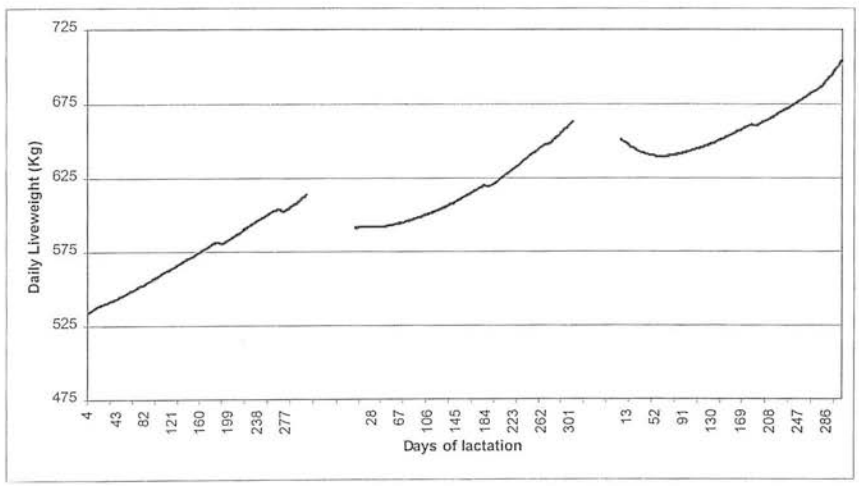


Figure 6.1d. Least squares mean condition score (CS units) for three lactations for all cows.

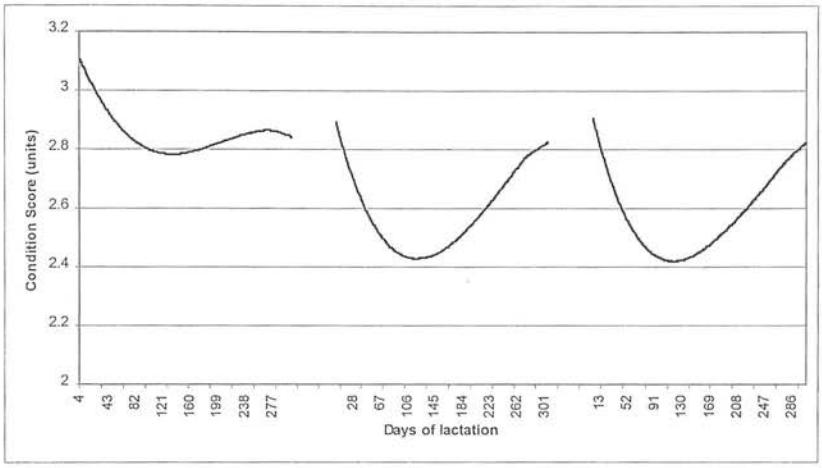


Figure 6.1e. Least squares mean energy balance (MJ) calculated from feed intake and milk output (EB1) for three lactations for all cows.

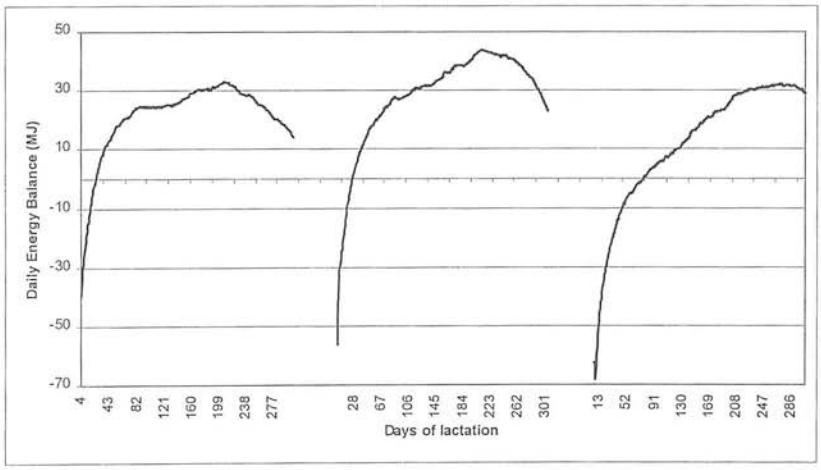


Figure 6.1f. Least squares mean energy balance (MJ) calculated from condition score and liveweight (EB2) for three lactations for all cows.

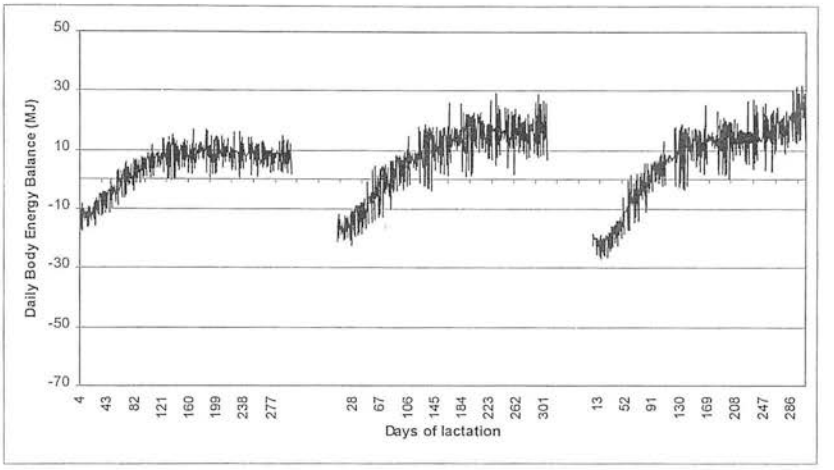


Figure 6.1g. Least squares mean cumulative energy balance (MJ) calculated from condition score and liveweight (EB2) for three lactations for all cows.

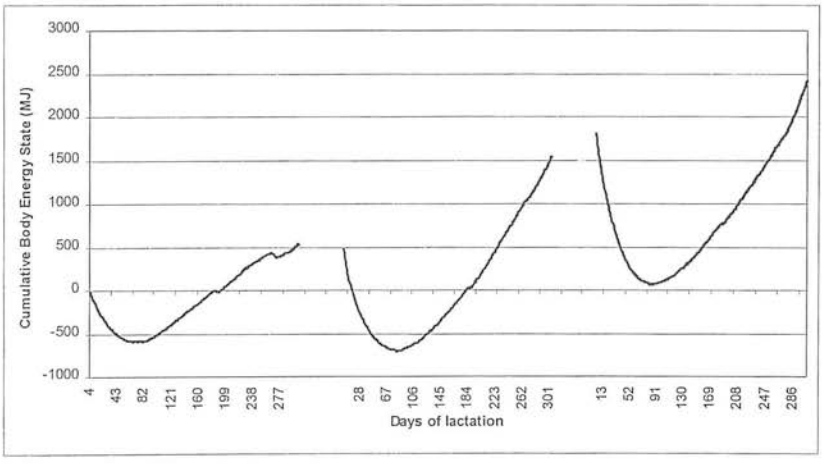


Figure 6.2a. Average milk yield (kg) by day of lactation for three lactations for cows in groups low concentrate control (-■-), low concentrate select (-□-), high concentrate control (-◆-) and high concentrate select (-◇-).

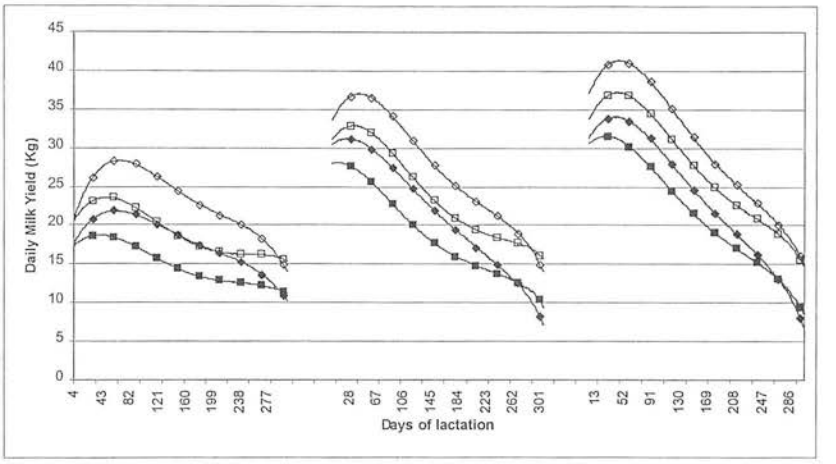


Figure 6.2b. Average fresh feed intake (kg) by day of lactation for three lactations for cows in groups low concentrate control (-■-), low concentrate select (-□-), high concentrate control (-◆-) and high concentrate select (-◇-).

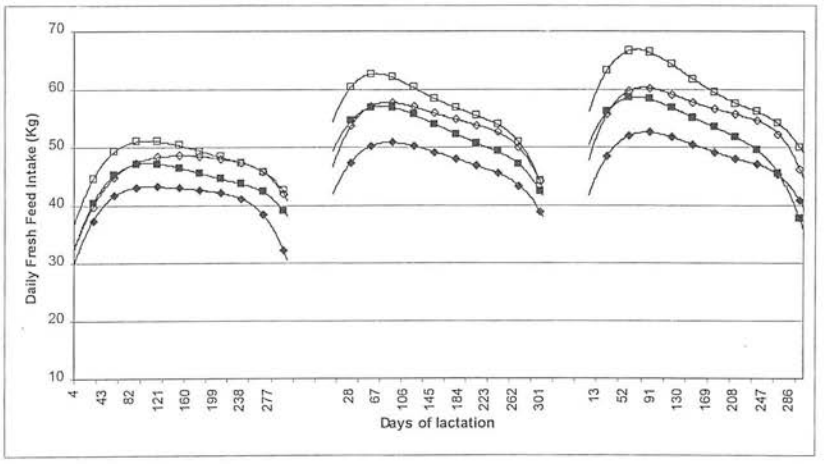


Figure 6.2c. Average liveweight (kg) by day of lactation for three lactations for cows in groups low concentrate control (-■-), low concentrate select (-□-), high concentrate control (-◆-) and high concentrate select (-◇-).

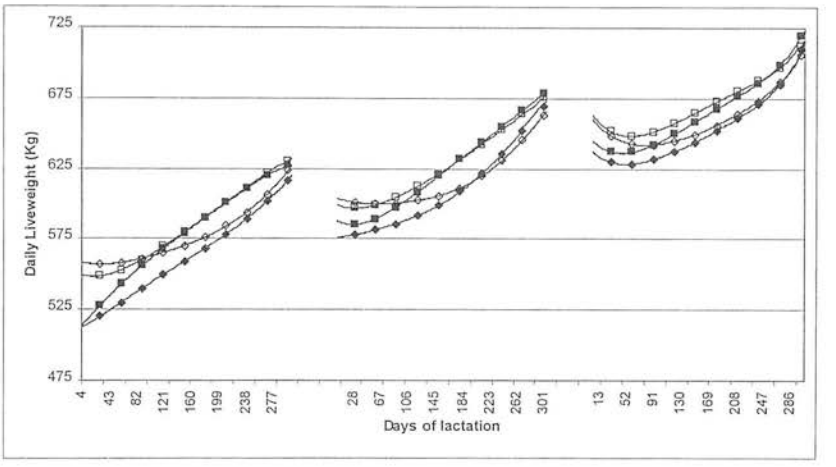


Figure 6.2d. Average condition score (units) by day of lactation for three lactations for cows in groups low concentrate control (-■-), low concentrate select (-□-), high concentrate control (-◆-) and high concentrate select (-◇-).

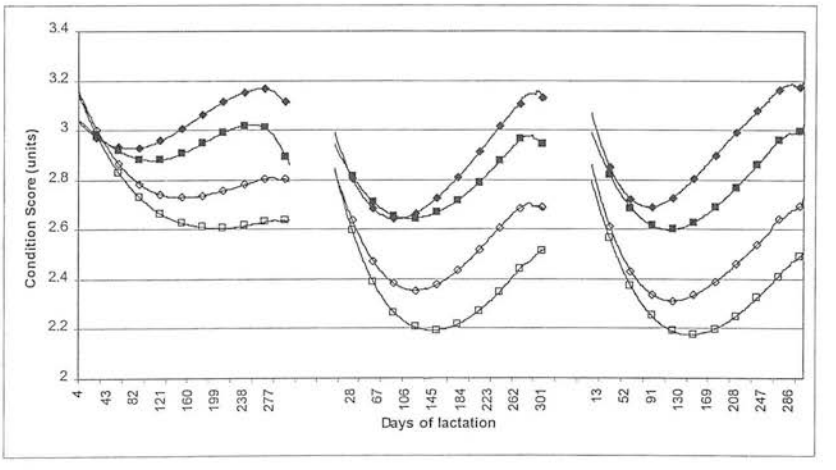


Figure 6.2e. Average daily energy balance (MJ) calculated from feed intake and milk yield by day of lactation for three lactations for cows in groups low concentrate control (-■-), low concentrate select (-□-), high concentrate control (-◆-) and high concentrate select (-◇-).

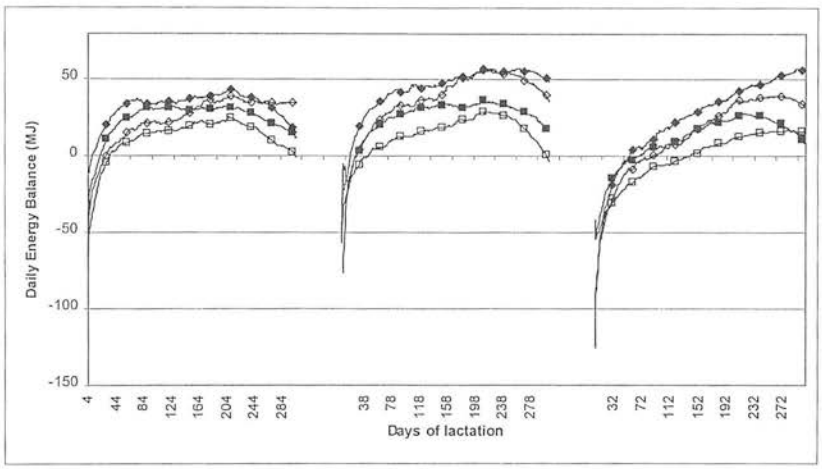


Figure 6.2f. Average cumulative energy balance from first calving (MJ) calculated from body energy changes by day of lactation for three lactations for cows in groups low concentrate control (-■-), low concentrate select (-□-), high concentrate control (-◆-) and high concentrate select (-◇-).

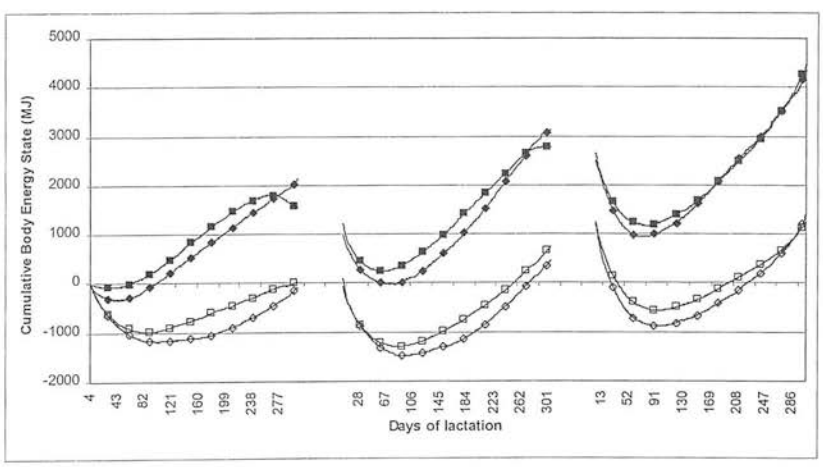


Figure 6.3a. First lactation liveweight (kg) for select cows that had a maximum of one (-▲-), two (-●-) or three (-*-) lactations of feed intake data on a low concentrate diet.

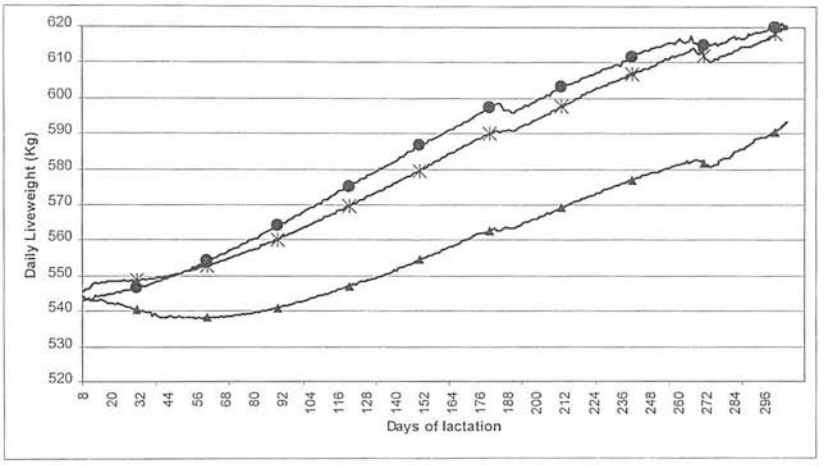


Figure 6.3b. First lactation condition score (units) for select cows that had a maximum of one (-▲-), two (-●-) or three (-*-) lactations of feed intake data on a low concentrate diet.

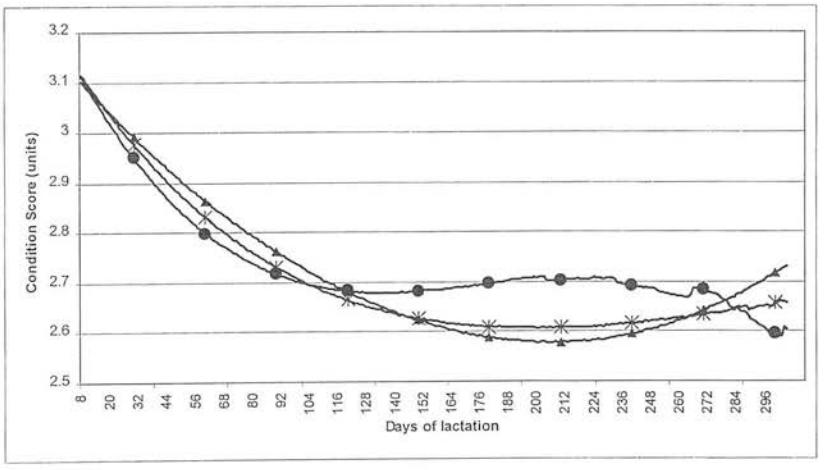


Figure 6.3c. First lactation cumulative body energy state (MJ) for select cows that had a maximum of one (-▲-), two (-●-) or three (-*-) lactations of feed intake data on a low concentrate diet.

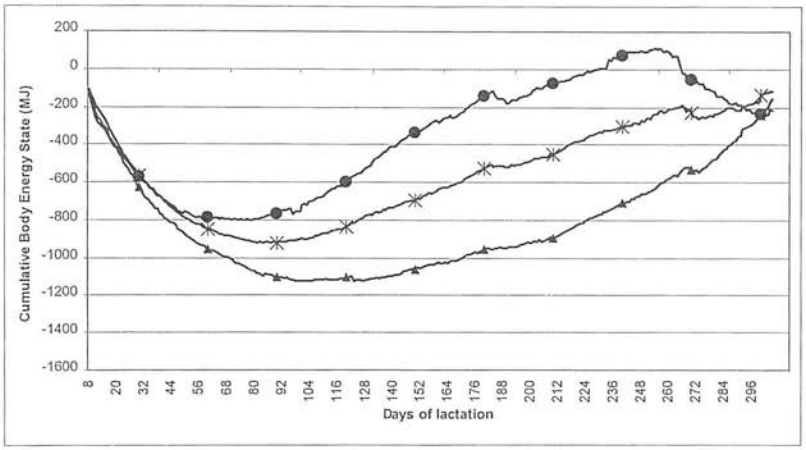


Figure 6.4a. First lactation liveweight (kg) for select cows that had a maximum of one (-▲-), two (-●-) or three (-*-) lactations of feed intake data on a high concentrate diet.

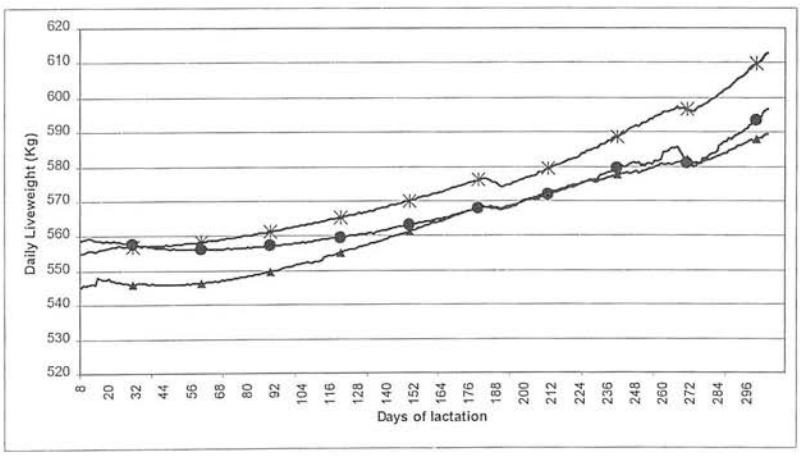


Figure 6.4b. First lactation condition score (units) for select cows that had a maximum of one (-▲-), two (-●-) or three (-*-) lactations of feed intake data on a high concentrate diet.

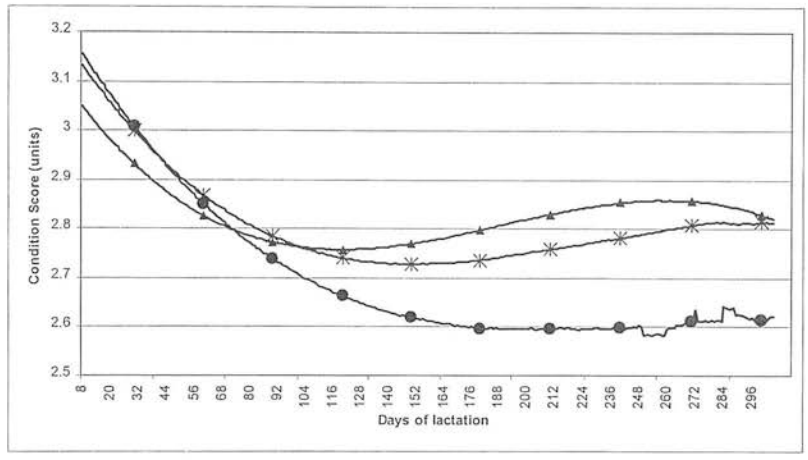
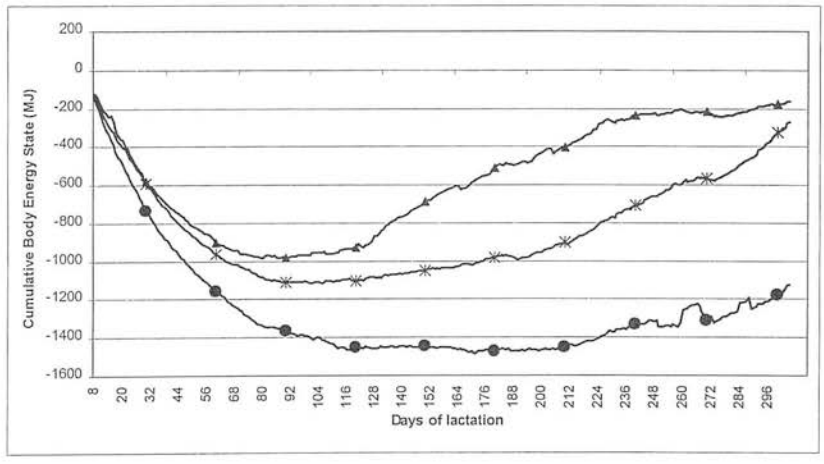


Figure 6.4c. First lactation cumulative body energy state (MJ) for select cows that had a maximum of one (-▲-), two (-●-) or three (-*-) lactations of feed intake data on a high concentrate diet.



6.7 Appendix B.

The orthogonal polynomial coefficients produced by ASREML are scaled depending on the version of the software used and the time period over which the data spans. Therefore, they are peculiar to each specific analysis and dataset and can only be compared to data from other analyses produced by the same version of ASREML and for the same range of timepoints. I have produced a sample set of coefficients in Table 6.3 for the analysis in this Chapter which is the most extensive analysis presented in this thesis.

Table 6.3. Orthogonal Polynomial coefficients for days of lactation 4 to 305 produced by ASREML for a fifth order fixed curve. Each coefficient is multiplied by the relevant regression coefficient from Table 6.4 and summed, along with the appropriate fixed effect regression coefficients, to produce the daily least squares solution.

Day	Coefficient 1	Coefficient 2	Coefficient 3	Coefficient 4	Coefficient 5
4	0.058	-0.099	0.127	-0.149	0.167
5	0.058	-0.099	0.125	-0.143	0.156
6	0.058	-0.098	0.122	-0.137	0.145
7	0.058	-0.097	0.120	-0.132	0.135
8	0.058	-0.097	0.117	-0.126	0.125
9	0.058	-0.096	0.115	-0.120	0.115
10	0.058	-0.095	0.112	-0.115	0.105
11	0.058	-0.095	0.110	-0.110	0.096
12	0.058	-0.094	0.108	-0.104	0.087
13	0.058	-0.093	0.105	-0.099	0.079
14	0.058	-0.093	0.103	-0.094	0.070
15	0.058	-0.092	0.100	-0.089	0.062
16	0.058	-0.091	0.098	-0.084	0.055
17	0.058	-0.091	0.096	-0.079	0.047
18	0.058	-0.090	0.093	-0.075	0.040
19	0.058	-0.089	0.091	-0.070	0.033
20	0.058	-0.089	0.089	-0.066	0.027
21	0.058	-0.088	0.087	-0.061	0.020
22	0.058	-0.087	0.084	-0.057	0.014
23	0.058	-0.087	0.082	-0.053	0.008
24	0.058	-0.086	0.080	-0.048	0.003
25	0.058	-0.085	0.078	-0.044	-0.003
26	0.058	-0.085	0.075	-0.040	-0.008
27	0.058	-0.084	0.073	-0.036	-0.013
28	0.058	-0.083	0.071	-0.032	-0.018
29	0.058	-0.083	0.069	-0.029	-0.022
30	0.058	-0.082	0.067	-0.025	-0.026
31	0.058	-0.082	0.065	-0.021	-0.030
32	0.058	-0.081	0.063	-0.018	-0.034
33	0.058	-0.080	0.061	-0.015	-0.038
34	0.058	-0.080	0.059	-0.011	-0.041
35	0.058	-0.079	0.057	-0.008	-0.044
36	0.058	-0.078	0.055	-0.005	-0.047

37	0.058	-0.078	0.053	-0.002	-0.050
38	0.058	-0.077	0.051	0.001	-0.053
39	0.058	-0.076	0.049	0.004	-0.055
40	0.058	-0.076	0.047	0.007	-0.058
41	0.058	-0.075	0.045	0.010	-0.060
42	0.058	-0.074	0.043	0.013	-0.062
43	0.058	-0.074	0.041	0.015	-0.064
44	0.058	-0.073	0.039	0.018	-0.065
45	0.058	-0.072	0.037	0.020	-0.067
46	0.058	-0.072	0.035	0.023	-0.068
47	0.058	-0.071	0.033	0.025	-0.069
48	0.058	-0.070	0.032	0.028	-0.070
49	0.058	-0.070	0.030	0.030	-0.071
50	0.058	-0.069	0.028	0.032	-0.072
51	0.058	-0.068	0.026	0.034	-0.073
52	0.058	-0.068	0.025	0.036	-0.073
53	0.058	-0.067	0.023	0.038	-0.074
54	0.058	-0.066	0.021	0.040	-0.074
55	0.058	-0.066	0.019	0.042	-0.074
56	0.058	-0.065	0.018	0.043	-0.074
57	0.058	-0.064	0.016	0.045	-0.074
58	0.058	-0.064	0.014	0.047	-0.074
59	0.058	-0.063	0.013	0.048	-0.073
60	0.058	-0.062	0.011	0.050	-0.073
61	0.058	-0.062	0.010	0.051	-0.072
62	0.058	-0.061	0.008	0.052	-0.072
63	0.058	-0.060	0.007	0.054	-0.071
64	0.058	-0.060	0.005	0.055	-0.070
65	0.058	-0.059	0.003	0.056	-0.069
66	0.058	-0.058	0.002	0.057	-0.069
67	0.058	-0.058	0.000	0.058	-0.067
68	0.058	-0.057	-0.001	0.059	-0.066
69	0.058	-0.056	-0.002	0.060	-0.065
70	0.058	-0.056	-0.004	0.061	-0.064
71	0.058	-0.055	-0.005	0.062	-0.063
72	0.058	-0.054	-0.007	0.063	-0.061
73	0.058	-0.054	-0.008	0.063	-0.060
74	0.058	-0.053	-0.009	0.064	-0.058
75	0.058	-0.052	-0.011	0.065	-0.057
76	0.058	-0.052	-0.012	0.065	-0.055
77	0.058	-0.051	-0.013	0.066	-0.053
78	0.058	-0.050	-0.015	0.066	-0.052
79	0.058	-0.050	-0.016	0.067	-0.050
80	0.058	-0.049	-0.017	0.067	-0.048
81	0.058	-0.049	-0.019	0.067	-0.046
82	0.058	-0.048	-0.020	0.068	-0.044
83	0.058	-0.047	-0.021	0.068	-0.042
84	0.058	-0.047	-0.022	0.068	-0.040
85	0.058	-0.046	-0.023	0.068	-0.039

86	0.058	-0.045	-0.025	0.068	-0.037
87	0.058	-0.045	-0.026	0.068	-0.034
88	0.058	-0.044	-0.027	0.068	-0.032
89	0.058	-0.043	-0.028	0.068	-0.030
90	0.058	-0.043	-0.029	0.068	-0.028
91	0.058	-0.042	-0.030	0.068	-0.026
92	0.058	-0.041	-0.031	0.068	-0.024
93	0.058	-0.041	-0.032	0.067	-0.022
94	0.058	-0.040	-0.033	0.067	-0.02
95	0.058	-0.039	-0.034	0.067	-0.018
96	0.058	-0.039	-0.035	0.066	-0.015
97	0.058	-0.038	-0.036	0.066	-0.013
98	0.058	-0.037	-0.037	0.066	-0.011
99	0.058	-0.037	-0.038	0.065	-0.009
100	0.058	-0.036	-0.039	0.065	-0.007
101	0.058	-0.035	-0.040	0.064	-0.005
102	0.058	-0.035	-0.041	0.063	-0.002
103	0.058	-0.034	-0.042	0.063	0.000
104	0.058	-0.033	-0.043	0.062	0.002
105	0.058	-0.033	-0.044	0.061	0.004
106	0.058	-0.032	-0.044	0.061	0.006
107	0.058	-0.031	-0.045	0.060	0.008
108	0.058	-0.031	-0.046	0.059	0.010
109	0.058	-0.030	-0.047	0.058	0.012
110	0.058	-0.029	-0.048	0.058	0.014
111	0.058	-0.029	-0.048	0.057	0.016
112	0.058	-0.028	-0.049	0.056	0.018
113	0.058	-0.027	-0.050	0.055	0.020
114	0.058	-0.027	-0.050	0.054	0.022
115	0.058	-0.026	-0.051	0.053	0.024
116	0.058	-0.025	-0.052	0.052	0.026
117	0.058	-0.025	-0.052	0.051	0.028
118	0.058	-0.024	-0.053	0.050	0.029
119	0.058	-0.023	-0.054	0.049	0.031
120	0.058	-0.023	-0.054	0.048	0.033
121	0.058	-0.022	-0.055	0.047	0.035
122	0.058	-0.021	-0.055	0.045	0.036
123	0.058	-0.021	-0.056	0.044	0.038
124	0.058	-0.020	-0.056	0.043	0.040
125	0.058	-0.019	-0.057	0.042	0.041
126	0.058	-0.019	-0.057	0.041	0.043
127	0.058	-0.018	-0.058	0.039	0.044
128	0.058	-0.017	-0.058	0.038	0.046
129	0.058	-0.017	-0.059	0.037	0.047
130	0.058	-0.016	-0.059	0.035	0.048
131	0.058	-0.016	-0.060	0.034	0.05
132	0.058	-0.015	-0.060	0.033	0.051
133	0.058	-0.014	-0.060	0.031	0.052
134	0.058	-0.014	-0.061	0.030	0.053

135	0.058	-0.013	-0.061	0.029	0.054
136	0.058	-0.012	-0.061	0.027	0.055
137	0.058	-0.012	-0.062	0.026	0.056
138	0.058	-0.011	-0.062	0.024	0.057
139	0.058	-0.010	-0.062	0.023	0.058
140	0.058	-0.010	-0.063	0.022	0.059
141	0.058	-0.009	-0.063	0.020	0.060
142	0.058	-0.008	-0.063	0.019	0.060
143	0.058	-0.008	-0.063	0.017	0.061
144	0.058	-0.007	-0.063	0.016	0.062
145	0.058	-0.006	-0.064	0.014	0.062
146	0.058	-0.006	-0.064	0.013	0.063
147	0.058	-0.005	-0.064	0.011	0.063
148	0.058	-0.004	-0.064	0.010	0.064
149	0.058	-0.004	-0.064	0.008	0.064
150	0.058	-0.003	-0.064	0.007	0.064
151	0.058	-0.002	-0.064	0.005	0.064
152	0.058	-0.002	-0.064	0.004	0.065
153	0.058	-0.001	-0.064	0.002	0.065
154	0.058	0.000	-0.064	0.001	0.065
155	0.058	0.000	-0.064	-0.001	0.065
156	0.058	0.001	-0.064	-0.002	0.065
157	0.058	0.002	-0.064	-0.004	0.065
158	0.058	0.002	-0.064	-0.005	0.064
159	0.058	0.003	-0.064	-0.007	0.064
160	0.058	0.004	-0.064	-0.008	0.064
161	0.058	0.004	-0.064	-0.010	0.064
162	0.058	0.005	-0.064	-0.011	0.063
163	0.058	0.006	-0.064	-0.013	0.063
164	0.058	0.006	-0.064	-0.014	0.062
165	0.058	0.007	-0.063	-0.016	0.062
166	0.058	0.008	-0.063	-0.017	0.061
167	0.058	0.008	-0.063	-0.019	0.060
168	0.058	0.009	-0.063	-0.020	0.060
169	0.058	0.010	-0.063	-0.022	0.059
170	0.058	0.010	-0.062	-0.023	0.058
171	0.058	0.011	-0.062	-0.024	0.057
172	0.058	0.012	-0.062	-0.026	0.056
173	0.058	0.012	-0.061	-0.027	0.055
174	0.058	0.013	-0.061	-0.029	0.054
175	0.058	0.014	-0.061	-0.030	0.053
176	0.058	0.014	-0.060	-0.031	0.052
177	0.058	0.015	-0.060	-0.033	0.051
178	0.058	0.016	-0.060	-0.034	0.050
179	0.058	0.016	-0.059	-0.035	0.048
180	0.058	0.017	-0.059	-0.037	0.047
181	0.058	0.017	-0.058	-0.038	0.046
182	0.058	0.018	-0.058	-0.039	0.044
183	0.058	0.019	-0.057	-0.041	0.043

184	0.058	0.019	-0.057	-0.042	0.041
185	0.058	0.020	-0.056	-0.043	0.040
186	0.058	0.021	-0.056	-0.044	0.038
187	0.058	0.021	-0.055	-0.045	0.036
188	0.058	0.022	-0.055	-0.047	0.035
189	0.058	0.023	-0.054	-0.048	0.033
190	0.058	0.023	-0.054	-0.049	0.031
191	0.058	0.024	-0.053	-0.050	0.029
192	0.058	0.025	-0.052	-0.051	0.028
193	0.058	0.025	-0.052	-0.052	0.026
194	0.058	0.026	-0.051	-0.053	0.024
195	0.058	0.027	-0.050	-0.054	0.022
196	0.058	0.027	-0.050	-0.055	0.020
197	0.058	0.028	-0.049	-0.056	0.018
198	0.058	0.029	-0.048	-0.057	0.016
199	0.058	0.029	-0.048	-0.058	0.014
200	0.058	0.030	-0.047	-0.058	0.012
201	0.058	0.031	-0.046	-0.059	0.010
202	0.058	0.031	-0.045	-0.060	0.008
203	0.058	0.032	-0.044	-0.061	0.006
204	0.058	0.033	-0.044	-0.061	0.004
205	0.058	0.033	-0.043	-0.062	0.002
206	0.058	0.034	-0.042	-0.063	0.000
207	0.058	0.035	-0.041	-0.063	-0.002
208	0.058	0.035	-0.040	-0.064	-0.005
209	0.058	0.036	-0.039	-0.065	-0.007
210	0.058	0.037	-0.038	-0.065	-0.009
211	0.058	0.037	-0.037	-0.066	-0.011
212	0.058	0.038	-0.036	-0.066	-0.013
213	0.058	0.039	-0.035	-0.066	-0.015
214	0.058	0.039	-0.034	-0.067	-0.018
215	0.058	0.040	-0.033	-0.067	-0.020
216	0.058	0.041	-0.032	-0.067	-0.022
217	0.058	0.041	-0.031	-0.068	-0.024
218	0.058	0.042	-0.030	-0.068	-0.026
219	0.058	0.043	-0.029	-0.068	-0.028
220	0.058	0.043	-0.028	-0.068	-0.030
221	0.058	0.044	-0.027	-0.068	-0.032
222	0.058	0.045	-0.026	-0.068	-0.034
223	0.058	0.045	-0.025	-0.068	-0.037
224	0.058	0.046	-0.023	-0.068	-0.039
225	0.058	0.047	-0.022	-0.068	-0.04
226	0.058	0.047	-0.021	-0.068	-0.042
227	0.058	0.048	-0.020	-0.068	-0.044
228	0.058	0.049	-0.019	-0.067	-0.046
229	0.058	0.049	-0.017	-0.067	-0.048
230	0.058	0.050	-0.016	-0.067	-0.050
231	0.058	0.050	-0.015	-0.066	-0.052
232	0.058	0.051	-0.013	-0.066	-0.053

233	0.058	0.052	-0.012	-0.065	-0.055
234	0.058	0.052	-0.011	-0.065	-0.057
235	0.058	0.053	-0.009	-0.064	-0.058
236	0.058	0.054	-0.008	-0.063	-0.060
237	0.058	0.054	-0.007	-0.063	-0.061
238	0.058	0.055	-0.005	-0.062	-0.063
239	0.058	0.056	-0.004	-0.061	-0.064
240	0.058	0.056	-0.002	-0.060	-0.065
241	0.058	0.057	-0.001	-0.059	-0.066
242	0.058	0.058	0.000	-0.058	-0.067
243	0.058	0.058	0.002	-0.057	-0.069
244	0.058	0.059	0.003	-0.056	-0.069
245	0.058	0.060	0.005	-0.055	-0.070
246	0.058	0.060	0.007	-0.054	-0.071
247	0.058	0.061	0.008	-0.052	-0.072
248	0.058	0.062	0.010	-0.051	-0.072
249	0.058	0.062	0.011	-0.050	-0.073
250	0.058	0.063	0.013	-0.048	-0.073
251	0.058	0.064	0.014	-0.047	-0.074
252	0.058	0.064	0.016	-0.045	-0.074
253	0.058	0.065	0.018	-0.043	-0.074
254	0.058	0.066	0.019	-0.042	-0.074
255	0.058	0.066	0.021	-0.040	-0.074
256	0.058	0.067	0.023	-0.038	-0.074
257	0.058	0.068	0.025	-0.036	-0.073
258	0.058	0.068	0.026	-0.034	-0.073
259	0.058	0.069	0.028	-0.032	-0.072
260	0.058	0.070	0.030	-0.030	-0.071
261	0.058	0.070	0.032	-0.028	-0.070
262	0.058	0.071	0.033	-0.025	-0.069
263	0.058	0.072	0.035	-0.023	-0.068
264	0.058	0.072	0.037	-0.020	-0.067
265	0.058	0.073	0.039	-0.018	-0.065
266	0.058	0.074	0.041	-0.015	-0.064
267	0.058	0.074	0.043	-0.013	-0.062
268	0.058	0.075	0.045	-0.010	-0.060
269	0.058	0.076	0.047	-0.007	-0.058
270	0.058	0.076	0.049	-0.004	-0.055
271	0.058	0.077	0.051	-0.001	-0.053
272	0.058	0.078	0.053	0.002	-0.050
273	0.058	0.078	0.055	0.005	-0.047
274	0.058	0.079	0.057	0.008	-0.044
275	0.058	0.080	0.059	0.011	-0.041
276	0.058	0.080	0.061	0.015	-0.038
277	0.058	0.081	0.063	0.018	-0.034
278	0.058	0.082	0.065	0.021	-0.030
279	0.058	0.082	0.067	0.025	-0.026
280	0.058	0.083	0.069	0.029	-0.022
281	0.058	0.083	0.071	0.032	-0.018

282	0.058	0.084	0.073	0.036	-0.013
283	0.058	0.085	0.075	0.040	-0.008
284	0.058	0.085	0.078	0.044	-0.003
285	0.058	0.086	0.080	0.048	0.003
286	0.058	0.087	0.082	0.053	0.008
287	0.058	0.087	0.084	0.057	0.014
288	0.058	0.088	0.087	0.061	0.020
289	0.058	0.089	0.089	0.066	0.027
290	0.058	0.089	0.091	0.070	0.033
291	0.058	0.090	0.093	0.075	0.040
292	0.058	0.091	0.096	0.079	0.047
293	0.058	0.091	0.098	0.084	0.055
294	0.058	0.092	0.100	0.089	0.062
295	0.058	0.093	0.103	0.094	0.070
296	0.058	0.093	0.105	0.099	0.079
297	0.058	0.094	0.108	0.104	0.087
298	0.058	0.095	0.110	0.110	0.096
299	0.058	0.095	0.112	0.115	0.105
300	0.058	0.096	0.115	0.120	0.115
301	0.058	0.097	0.117	0.126	0.125
302	0.058	0.097	0.120	0.132	0.135
303	0.058	0.098	0.122	0.137	0.145
304	0.058	0.099	0.125	0.143	0.156
305	0.058	0.099	0.127	0.149	0.167

Table 6.4. Regression coefficients for fixed quartic polynomial curves for control line cows for Milk, Feed Intake, Body Condition Score (BCS) and Liveweight on a high (HC) and low (LC) concentrate diet for the analysis in Chapter 6. Coefficient 1 is the intercept, 2 the slope etc.

	Milk		Feed Intake		BCS		Liveweight	
Coefficient	HC	LC	HC	LC	HC	LC	HC	LC
Lactation 1								
1	49.280	0.000	-53.410	0.000	1.550	0.000	-255.00	0.000
2	-48.160	-40.140	-11.210	-1.654	1.641	0.644	440.10	527.70
3	-15.420	4.040	-65.320	-51.930	0.351	0.503	-44.290	-84.370
4	6.150	6.229	0.833	15.200	-0.608	-0.703	1.408	-5.730
5	-9.434	-7.241	-18.520	-13.430	-.0459	-0.231	14.640	-0.051
Lactation 2								
1	41.660	0.000	67.640	143.60	1.511	0.000	-215.60	0.000
2	-119.50	-93.050	-31.980	-54.830	2.503	1.397	385.60	463.70
3	-5.950	11.780	-41.030	-30.500	1.718	1.661	92.510	30.350
4	0.103	-1.645	6.559	12.400	-0.927	-0.561	8.958	-33.260
5	-10.290	-10.64	-12.920	-13.370	0.021	-0.095	5.191	24.000
Lactation 3								
1	31.080	0.000	91.910	151.70	2.624	0.000	-165.20	0.000
2	-135.700	-119.30	-29.920	-78.620	2.373	1.282	305.50	353.20
3	-17.450	-1.337	-40.650	-50.940	1.565	1.991	104.70	78.560
4	6.751	4.274	14.330	1.444	-1.027	-0.649	5.724	-13.710
5	-13.750	-11.500	-15.570	-18.670	0.1630	-0.054	33.400	37.140

Table 6.5. Regression coefficients for fixed quartic polynomial curves for select line cows for Milk, Feed Intake, Body Condition Score (BCS) and Liveweight on a high (HC) and low (LC) concentrate diet for the analysis in Chapter 6.

	Milk		Feed Intake		BCS		Liveweight	
Coefficient	HC	LC	HC	LC	HC	LC	HC	LC
Lactation 1								
1	147.10	93.780	52.650	72.480	-3.248	-4.177	-120.70	51.860
2	-49.210	-50.890	32.600	1.661	-1.099	-1.814	246.30	391.20
3	-27.980	8.641	-53.310	-42.260	1.350	1.431	74.270	20.990
4	16.420	13.410	14.520	19.410	-0.482	-0.358	7.715	-34.140
5	-14.080	-9.552	-11.590	-12.990	-0.007	0.015	15.860	14.640
Lactation 2								
1	153.60	109.90	187.10	223.00	-5.056	-7.520	-272.60	-22.920
2	-112.50	-97.390	-34.410	-71.090	0.777	-0.394	207.80	358.80
3	-8.307	10.830	-48.760	-36.400	2.208	2.543	113.90	51.960
4	11.220	12.000	8.137	7.474	-0.909	-0.590	22.490	-26.120
5	-16.630	-12.860	-18.620	-20.430	-0.112	0.036	10.350	12.950
Lactation 3								
1	156.900	117.10	224.70	280.90	-5.569	-7.613	-198.20	32.380
2	-133.200	-117.50	-33.730	-70.160	0.479	-0.519	197.70	245.00
3	-14.750	-7.449	-47.360	-35.430	2.368	2.451	138.70	74.290
4	16.520	14.460	12.120	20.910	-0.802	-0.548	-4.124	-30.420
5	-15.540	-14.530	-21.680	-18.060	0.090	-0.002	28.190	36.240

Chapter 7

General Discussion

7.1 Introduction

Selection for production has led to cows that mobilise a greater proportion of their body tissue to support lactation (Veerkamp et al., 1995). As well as selection for production, breeders and AI companies have additionally selected for Angularity (Dairy Form) and modern cows are associated with being high producing and relatively thin in appearance. This has consequences for both health and fertility since body condition score (BCS) is unfavourably correlated with fertility (Pryce et al., 2001) and some health traits (Collard et al., 2000). The unexpected and unacceptable correlated responses to selection primarily for production suggests that an enhancement of selection indices is required to counteract these changes, or at least to prevent further decline. One of the aims of this thesis was to investigate ways in which body lipid content may be incorporated in future selection indices to improve overall health and fertility. In this thesis, BCS is used as a proxy for body energy status and its change and the cyclical changes in BCS over the course of the first three lactations was investigated in Chapter 4 and 6 using data from an experimental farm where BCS was recorded weekly on all cows. Given the potential use of BCS in future selection indices, an automated method of collecting records on BCS was investigated in Chapter 2 and a genetic analysis in Chapter 5 showed that there is substantial genetic variation between sires in the profiles of body tissue loss and gain of their daughters. This suggests that BCS or an aspect of its change may prove a useful addition to a broader breeding index in the future that more fully accounts for profitability of production.

7.2 Body Condition Score and body lipid content

Body condition score is a good predictor of body fat reserves in Holstein-Friesian dairy cattle (Fox et al., 1999). In a serial slaughter experiment Gibb and Ivings (1993) derived by regression analysis, formulae describing fat and crude protein (CP) content of dairy cows as a function of BCS and liveweight (LWT). Not accounting for gut fill represents a major barrier to the use of these prediction equations when calculating daily energy contribution from body tissue on an individual cow basis. In all analyses presented in this thesis, a formula derived from the data of Wright (1982) that predicts body lipid content from empty body weight was used (Appendix A, Chapter 3) thereby removing the effect of gut fill. However, this formula does require prediction of empty body weight and so some

estimation of gut fill. Gut fill was predicted from feed characteristics and changes in the predicted composition of the feed created the 'jagged' appearance of the body energy state curves produced using random regression. Future analyses should consider removing the effect of gut fill before analysing changes in what would then be empty body weight.

The analyses of Gibb et al. (1992) were carried out on a sample of the UK cow population at a time when a rapid breed substitution was occurring but was not complete (Chapter 1). For example, the average production of cows used in their study ranged from 4000 to 6000 kg milk for second lactation animals and 5000 to 7000 kg for older cows. The mean BCS was 2.6 and ranged from 1.92 to 3.24. Such cows and yields are not representative of today's cow population where the current mean yield is 7179, 8140 and 8540 for lactations 1, 2 and 3 respectively for Holstein-Friesians calving in 2000 to 2001 (National Milk Records, 2003). It would help future research on the use of body lipid in dairy cows if body compositional analysis were to be repeated using modern larger, higher yielding cows of a wider range of BCS, particularly at lower values of BCS. Since the total amount of fat in a cow is a function of both weight and BCS, it follows that heavier cows have a greater amount of body lipid at the same BCS. Alternatively, modern cows can appear to be thinner (lower BCS) and still contain the same amount of body energy if the relationships between BCS and body energy content translate from Friesians to Holsteins.

Given that the current UK cow population is based predominantly on North American genotypes and their close derivatives, results from an experiment by Komaragiri et al. (1998) are relevant to the UK population. They showed, by regression analysis, that changes in body lipid accounted for 99% of energy gained or lost in second lactation cows. This is particularly important when attempting to estimate energy released by body tissue mobilisation as indicated by LWT and BCS changes in early lactation although it ignores the lipid free part of growth in a first lactation cow. The serial slaughter work of Gibb et al. (1992) showed that empty body weight decreased to week 8 *post partum* and then increased subsequently but that some organs were increasing in weight while others were decreasing. Therefore, some of the change in BCS in early lactation is used to provide energy not only for production but also for growth of internal organs, such as the liver.

Since lipid and protein require different amounts of energy for metabolism and catabolism, it is important to account for the changes in the relative amounts of these when calculating energy contributed by body tissue. This was tested in Chapter 3 where the Effective Energy system proposed by Emmans (1994) which has in-built scaling factors for energy source (see Appendix A in Chapter 3) was used. In this energy system, energy released or needed for changes in protein content was on the same scale as that for lipid. In Chapter 3, I compared energy balance calculated using body energy estimates (EB2) to that calculated directly from feed intake measures and milk output (EB1). This was to determine the usefulness of BCS and LWT measured in the field where feed intake measures do not exist. Whilst there are differences, they are not large and they might be explained by sources of error such as wasted feed or error in prediction of feed composition. In particular, the assumption of constancy in digestibility of feed at high levels of feed intake may not be correct and future analyses should test this. A test could be to determine how much the error in prediction of feed intake and digestibility need to change in order to reduce the difference between EB1 and EB2 to non-significance for cows that have EB1 and EB2 estimated at the same time.

7.3 Body lipid and selection indices.

The relative economic value (REV) for the production components of the UK profit index £PLI, include the costs associated with feed and quota and the REV for lifespan includes costs due to culling (excluding culling for low production). However, £PLI does not yet include other costs such as those directly associated with disease e.g. mastitis. In particular, and within the context of this thesis, for bulls' daughters that mobilise body tissue in support of lactation, the contribution of body energy to milk production in the same or subsequent lactations is not accounted for even though it can be large, as demonstrated in Chapters 4 and 6. In Chapter 6, results show that select (S) cows offered a high concentrate diet had approximately 3200 MJ less body energy at the end of lactation 3 than control (C) cows offered the same diet. This is a partitioning strategy of S cows associated with satisfying the need for energy for production at a higher priority than that of body energy. However, given that continued selection for production at the current selection intensity is likely to continue the trend of

partitioning away from body energy and towards production, at what point does this strategy of partitioning become a cost and not a contribution to output?

The moderate heritability of BCS and the marked differences between sire progeny groups in the shape of the BCS profile throughout lactation, offers a possibility of including BCS or BCS change in a profit index either as a predictor of a trait with economic importance such as disease or longevity or in its own right as a measure of energy status. For example, for bulls with equal genetic merit for production, the average breeding value for BCS could be a predictor of the average energy intake of the daughters. Genetic merit for energy balance calculated from available national data on predicted LWT and BCS was estimated in Chapter 5. Results showing genetic variation in energy balance profiles for sires' daughters suggest that future indices could contain estimates of genetic merit for body lipid content or changes in body lipid content. An attempt at quantifying the contribution of body energy to production on the ranking of bulls for milk production was made by subtracting the milk kg equivalent to the energy contributed by body lipid change but this only accounted for the direct contribution of body energy to production. Other parameters of the curve might potentially be more informative although, as a matter of principle, the use of BCS in a selection index in this way will allow future measures of utility to include inputs as well as outputs which may be more important if government policy requires reduced environmental impact of dairy farming.

Given the relationship between body energy mobilisation and health disorders (Veerkamp et al., 2000; De Vries et al., 2000; Collard et al., 2000; Pryce et al., 2001) there is likely to be a REV for body energy that is associated with health. In order to include body energy contribution in future selection indices, an understanding of the phenotypic and genetic parameters of body energy and body energy change is required along with genetic correlations with health and fertility traits. This is to avoid double counting since BCS is expected to be included in a new UK fertility index as a predictor of fertility.

7.4 Body condition scoring

Body condition score is now recorded in a number of other countries in much the same way as in the UK (using field recorders and visual assessment) and as part of other national recording activity. This indicates wider acknowledgement of its use either as a management aid or potentially, for use as a selection aid. An automated method of recording BCS would enable the collection of a large volume of serial data on BCS and allow a closer study of the effects of change in BCS, and other parameters of BCS or its change, on a number of economically important traits such as production, health, fertility and survival. Perhaps more importantly, it would enable continuous recording on the same animals over many lactations and potentially provide data for more complex lifetime-based selection indices at the sire level.

Such a method must be robust, remote and produce data that is related to body energy content. In Chapter 2, I investigated (in conjunction with others at Silsoe Institute) the feasibility of extracting shape information from images taken using a digital camera and then correlating that shape with BCS. This technique warrants further effort to develop a method that could be used commercially. A successful system would embed current expertise on visual assessment of BCS into software and use collateral information, such as daily yield and previous BCS, to improve the prediction of BCS on a daily basis.

7.5 Body fat content and health

Improved management may only be able to overcome some of the apparent phenotypic decline in fertility since Pryce et al. (1999) demonstrated a genotype by diet interaction for fertility. In this study, cows selected for production had a 2 day increase in days to first oestrus on a high concentrate diet compared to those on a low concentrate diet suggesting that improved feeding made fertility worse. Furthermore, selected cows had a lower BCS and a greater loss of lipid in early lactation. In another study, the same authors showed that cows with a lower BCS had a longer calving interval. The genetic correlation between BCS and CI was –0.48 and even after adjusting for milk yield, the correlation was –0.22 (Pryce et al., 2002). This implies that continuing selection for yield alone will lead to cows that

are thinner, will respond to increased inputs by increasing production and as a result, will have a longer CI, all of which may not be desirable outcomes for UK producers.

Rogers et al. (1999) showed that bulls with a high score for Dairy Character (Dairy Form in the USA) have daughters with a higher level of lameness, metabolic disease and reduced fertility. Pryce et al. (2000) reported a high correlation between BCS and Angularity (dairy character). High scores for Dairy Character and Angularity may therefore be associated with low BCS and the associated higher incidence of disease. This represents a problem and a challenge for breeders and AI companies since high scores for overall type in the UK are associated with high scores for Angularity. A selection index that favours Angularity as well as production is likely to increase health and fertility problems in high yielding cows.

The correlation between incidence of different diseases post-partum is moderate, e.g. 0.41 between mastitis and services per conception and 0.44 between lameness and mastitis (Kadarmideen et al., 2001). This suggests that selection against incidence of one disease will have positive correlated responses in other diseases and raises the possibility of using BCS as a proxy trait for higher general health and using BCS in a multi-trait index for selection in dairy cows.

7.6 Genetic versus management induced negative energy balance

The genetic variation in bulls' daughters for BCS (Jones et al., 1999; Chapter 3; Chapter 5) and for daily energy balance (Chapter3) and the moderate heritability for BCS demonstrate that part of the energetic status of the cow is under genetic control. The metabolic systems active within a cow that is in negative energy balance as a result of either deliberate or unintentional management policies may be different from that of a cow in the same state as a result of her genetic merit for fatness. Animals inappropriately fat or thin in relation to their genotype and stage of lactation may produce different nutrient partitioning responses when management systems are altered. Low yielding animals poorly fed may be physiologically different to genetically high yielding animals well fed but still in negative energy balance. An experiment to test this would be to create groups of animals in the same lactation that are of high and low genetic merit for BCS and through management, make them phenotypically

thin and fat. After a period of stabilisation, a change in nutrient density would create a change in yield and BCS that may be an effect of the differing partitioning responses in relation to their metabolic status. Another useful experiment would be to monitor cortisol levels in animals in the different groups in different degrees of negative energy balance. This may provide information on the general level of 'stress' associated with metabolic status.

7.7 Manipulation of Lactation Curve Shape or selection for energy balance?

The outcome of competition within the cow for available nutrients results in the lactation curve shape and the shapes of curves of other traits affected by nutrient availability such as BCS, LWT and, ultimately, energy balance. Unfortunately, cause and effect, in terms of the concurrent changes in each of these traits, are unknown for these traits.

The shape of the lactation curve may have an impact on future profitability and may itself be affected by previous lactations. In a review of the genetics of lactation persistency, Swalve and Gengler (1999) suggest the economic significance of persistency may be related to its impact on metabolic stress and thereby health and fertility traits rather than on feed costs or production alone. They also suggest that future studies should involve both geneticists and physiologists because of the confounding effect of persistency on metabolic stress. Interestingly they suggest that the inclusion of persistency in selection programs is premature until more studies are undertaken investigating the relationship of persistent lactations with, for example, survival.

A given lactation yield requires a predictable amount of energy to pass through the cow and so a more persistent lactation has consequences for body tissue mobilisation and replenishment in that lactation. The dry period is used to prepare for the next lactation and replenishment of body tissue during the dry period is less efficient than during lactation. Lactation persistency and energy balance profile would therefore appear to be correlated. In order to select for both lactation persistency and appropriate body energy content at critical stages of lactation, breeding values for both that describe changes in genetic merit as a function of time are needed. Milk yield is already collected in this way

and is soon to be evaluated in the UK using a test day model. These methods of analysis would allow other useful traits such as energy balance to be evaluated similarly.

The first lactation while the animal is still growing adds another level of competition for nutrients. However, the appropriate use of body lipid may provide a nutritional advantage to the high yielding cow while feed intake catches up with demand. The appropriate severity and duration of negative energy balance to optimise life expectancy and yield has not yet been modelled and Chapters 4 and 6 are, to my knowledge, the first published results for more than two lactations of data for the same cows. In Chapter 4, I attempted to fit a continuous function using sines and cosines to energy balance throughout three lactations. While only accounting for about 45% of the variation in energy balance, this function was significantly better than a straight line and suggests that the shape of the energy balance curve over the animal's lifetime may be included in a selection index. Further effort is required to improve modelling of lifetime energy balance curves with a view to finding the optimal shape for maximal lifetime profitability where the animal has sufficient body lipid at critical points such as pregnancy and appropriate or acceptable amounts at other times.

7.8 Energy balance and welfare

In Chapters 4 and 6, results show that the rate of body tissue loss over lactations is greater for select animals than control animals leading to a divergence of BCS at calving over successive lactations. Select cows at the end of lactation 3 had significantly less body energy and were of significantly lower BCS. The rate of divergence seen between S and C cows may be a part of the explanation for the decrease in health and fertility seen in modern high yielding dairy cows.

If selection in dairy cows continues with the current goal that emphasises production, it is likely that future generations of cows will lose more of their body energy earlier in their lives perhaps leading to lower herd survival. As well as economic and environmental implications of lower survival, there are welfare and ethical considerations. The latter may override economic implications. For example the Banner Committee report (1995) suggested that the use of cost/benefit ratio tests cannot be used as the

sole measure of the acceptance of a position. Selection for thinner cows may not be acceptable in future.

Restricted indices are not favoured by many in animal breeding since they do not allow for optimisation across traits. However, for some traits for which there is no easily identified economic value, such as body energy content, there may be an argument for establishing a 'societal' lower threshold of body energy content that is acceptable in terms of actual or perceived welfare of the animal. However, as expected, there are economic costs in terms of a reduction in the rate of increase in milk yield for dairy cows selected on milk yield with BCS restricted to no change (Pryce et al. 2002).

Genetic thinness (or fatness) and phenotypic thinness have different consequences post-partum since increasing the fat content of genetically thin cows at parturition may lead to increased fat loss in early lactation thereby exacerbating the problem of reduced health and fertility. This was demonstrated by Garnsworthy and Webb (1999) where they summarised data from a number of experiments and showed that loss of body condition *post partum* is related to BCS at parturition. Cows that are fatter lose more than cows that are thinner suggesting that cows may have a target BCS post-calving. There is an interaction between genetic fatness and phenotypic fatness in the way that cows approach that target, potentially leading to thin cows at calving actually gaining lipid from the start of lactation.

Holter et al. (1990) also showed that cows calving in a lower condition score (thin group) mobilised less body tissue *post partum* and had lower fat percentages in their milk during their testing period. However when the complete lactation was analysed, there was no difference between the thin or fat group for milk, protein and SNF yield, DMI or nutrient utilisation. This reinforces the suggestion of Garnsworthy and Webb, (1999) that some of the 'welfare' problems of health and reproduction associated with postpartum body weight loss may be alleviated by keeping cows in a lower average condition score during the dry period.

In a review of the undesirable effects of selection for production, Rauw et al. (1998) cite over 100 references that relate undesirable (cor)related responses to selection for production in farmed livestock. In sows that had been selected for increased growth rate and backfat thickness, the interval from weaning to oestrus was extended. Gilts with a higher lean percentage had delayed onset of puberty, which may be in part related to selection for leanness increasing the mature body weight of pigs (Whittemore et al., 1994). Boars selected for high lean tissue growth rate had more leg weaknesses than non-selected boars. The authors state that the relationship between selection for high yield and health disorders is not clear due to the multi-factorial nature of disease occurrence.

However, Rauw et al. (1998) go on to speculate that single trait selection may have led to the situation where available resources are preferentially allocated to the trait under selection, leading to a lower proportion of resources being available to other functions, particularly those such as immunity that may be called upon as a result of a challenge. The authors conclude that future selection goals should be broadened to include traits of importance to the animal and that breeders will have to accept a lower rate of increase in production. Also, more work is required to understand the biological pathways affected by selection.

Lawrence et al. (2001) go further and suggest that animals should be selected using breeding goals that incorporate 'welfare' traits and should subsequently be matched to their environment in order to exploit genotype by environment interactions. This would mean selecting animals suited to their environment rather than selecting those that can cope with their environment. Translated to dairy cows, this would suggest that selection for thin and fertile animals would be unacceptable since thinness is associated with increased disease incidence and presumably, lower welfare.

These views combine to suggest that a programme of work is required to investigate the traits underlying what might be termed 'robust' cows. These are those that can sustain high yields over many lactations and can become pregnant at the first insemination with a low incidence of disease. If the biological characteristics of such cows could be identified, then a suitable selection pathway could be developed.

7.9 Gene expression

The change in heritability of BCS over the course of lactation (Jones et al., 1999) leads on to questions regarding the mode of action of genes in creating the profiles of lactation, growth and BCS. Do animals get fat(ter) at the end of lactation simply because there are 'spare' nutrients circulating in the blood? This would suggest that lipid stores are simply deposits for spare nutrients. Does milk yield decline because the lipid stores have been depleted and need repletion? This would be implicit in the idea that the lipid stores are not passive organs and that the animal has a long-term strategy that requires lipid to be stored to certain levels at certain stages. In the wild, animals would reproduce approximately annually in order to take advantage of seasonal food availability, but cyclical food availability is less important to dairy cows that have been selected for production and kept in modern management systems and so the relationship between reproduction, lactation and body tissue changes may have been uncoupled. Trayhurn and Beattie (2001) describe adipose tissue 'as an endocrine and secretory organ' asserting that adipose tissue plays an active role in regulating many important physiological pathways. Work is required to understand the actions of genes controlling body lipid content over the course of lactation and pregnancy and the interaction between these genes in species such as dairy cows that lactate while pregnant and that have been altered by selection for production.

Failure to secure sufficient nutrients may render some metabolic systems incapable of proper functioning e.g. reproduction and immune responsiveness. The combined outcome of the actions of genes controlling nutrient uptake by these competing systems creates a 'ranking' for nutrient demand. These rankings must change over lactation and gestation (with a possible interaction) and be a function of previous partitioning. Such changes in ranking may be under genetic control making them potential targets for selection.

7.10 Cross Generation Effects

Maternal environment may affect subsequent performance of offspring by altering cell division and differentiation at specific embryonic or foetal development 'windows' (for a review see Robinson et al., 1999). For example, maternal under-nutrition in sheep produced delayed ovarian follicular

development in the foetus (Rae et al., 2001). Since there is a large amount of cell division and differentiation in early gestation, it seems plausible that the maternal environment may have considerable effects on major developmental events early in gestation.

It is easy to speculate that this may be relevant to dairy cows since they are made pregnant at or around peak yield and in the period of greatest cumulative energy loss (Chapter 4 and 6). At this point of the lactation, the developing embryo is experiencing a maternal environment similar to one of extreme nutrient scarcity. The restriction of food to mice during gestation produced daughters that had less ability to invest in offspring according to Meikle and Westberg (2001) confirming that maternal environment may produce effects in the productive capacity of offspring.

If the proposition that the developing foetus uses its maternal environment as a measure of the nutritional environment it will eventually experience has any basis, we can speculate that the foetus may alter its own partitioning priorities to favour body lipid rather than body protein. However, this means the resulting offspring would then favour partitioning towards body tissue, would therefore have a lower yield and thus create a favourable maternal environment for its own foetus. This phenomenon was observed during the Dutch famine of 1944-1945 where offspring of mothers undernourished in early gestation that were then adequately nourished in later gestation, were longer and heavier at birth but were at higher risk of obesity in later life (Roseboom et al., 2000). It has been postulated that prolactin and its receptor may be part of the unifying mechanism whereby foetal development is modified in response to the mothers changing environment in sheep (Symonds et al. 2001).

The maturity of modern Holsteins at first calving and subsequently during the first lactation may create a maternal environment that is detrimental to the developing foetus, particularly if the cow is producing large amounts of milk and may be in negative energy balance for a large part of the first lactation (Chapter 3). Such a maternal environment would be characterised by high levels of IGF-1 and low levels of Insulin favouring milk production and protein anabolism. How this maternal environment affects the offspring is unknown. The effect of maternal environment on subsequent

performance could be tested in dairy cows using national data by looking to see if fitting the relationship between daughter/grandmother accounts for more variation in sire PTAs for production than does fitting the daughter/mother relationship. However, in a study investigating the effect of maternal environment of daughter fertility, Pryce et al., (2002) found no significant effect of yield, feed intake, parity or BCS on daughter fertility. The authors suggest lack of significance in their results could be due to low numbers of records (389 heifer records) or a small difference in the maternal environments experienced at Langhill.

Robinson et al. (1999) reviewed the effects of maternal nutrition on foetal growth and reported that placental growth in early lactation affects the subsequent growth of the foetus independent of late gestation nutrition by altering the subsequent partitioning between maternal body and gravid uterus. The increasing negative energy balance of high yielding cows in early lactation and around pregnancy may be programming the foetus and its development thereby creating longer-term effects than are at present being considered. The impact of the maternal environment on subsequent generations' performance needs to be studied more closely in dairy cows and could lead to feeding and breeding regimes that balance the current needs of the mother with the needs of the developing foetus. However, the effect of maternal environment on fetal programming of adipose tissue needs to be further elucidated in dairy cattle.

7.11 Conclusions

This thesis has demonstrated that, by estimating breeding values for energy balance, body energy change may be used in future selection indices. It has revealed for the first time the progressive reduction in body lipid content over three lactations in cows selected for production. Our previous selection policies have enjoyed this contribution to production for 'free'. Future selection strategies pursued by breeding companies are likely to continue to favour yield. Market signals exerted by the semen buying decisions of farmers may encourage a broader breeding goal to be considered by AI companies. Future government policy regarding the environmental impact of dairying will encourage farmers to reduce the wastage of dairy cows and reduce the numbers of followers required to maintain a dairy herd. Each ruminant contributes greenhouse gases such as methane simply to maintain itself

and so reducing the total number of ruminants will lead to a reduction in methane production from dairying. Such pressure will dictate that breeding goals in future take account of inputs as well as outputs and energetic efficiency of the whole farm system will need to be improved. The optimal productive life and number of lactations required to maximise energetic efficiency of whole management systems is currently unknown and may vary by system. The role of genetics in contributing to the improvement in farm system energetic efficiency is only now being considered and requires a shift in selection emphasis from single lactation to whole lifetime performance. The challenge for breeders is to produce a robust cow that survives in the herd with high health at high yield levels and that reproduces at the desired time. The challenge for dairy farmers is to farm at higher energetic efficiency with lower environmental impact and improved animal welfare standards. Incorporating body energy loss and gain in a broader breeding goal may help in this quest.

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